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THE PREDICTABILITY OF WIND AND VIRTUAL TEMPERATURE PROFILES FOR FLIGHT AND STATIC TEST OPERATIONS

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Prepared under Contract NAS8-20234 by

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THE TRAVELERS RESEARCH CENTER, INC.
250 Constitution Plaza Hartford, Connecticut 06103

For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

March 1966

S67-39657

Contract NAS8-20234

THE PREDICTABILITY OF WIND AND VIRTUAL TEMPERATURE PROFILES FOR FLIGHT AND STATIC TEST OPERATIONS

FINAL REPORT

July 1, 1965—March 31, 1966

Keith W. Veigas
David B. Spiegler
John T. Ball
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FORWARD

The work reported here was performed under Contract No. NAS8-20234 for the NASA/George C. Marshall Space Flight Center. The contract monitor was Mr. O. E. Smith. This report concludes Contract No. NAS8-20234.

ACKNOWLEDGEMENTS

The authors thank the NASA/MSFC personnel, particularly Mr. O. E. Smith and Mr. W. W. Jones, for providing guidance on important aspects of the wind and temperature profiles relative to the operational problems.

The data used in this study were supplied by several government agencies. NASA/MSFC supplied observed and predicted velocity of sound profiles in addition to processing FD's through their ray-tracing model. WINDS data from NASA/KSFC were helpful in examining the diffusion prediction problem. NMC provided a sample of FD's and the upper-air station data used in the evaluation of jet-stream prediction techniques. The multi-level numerical model predictions were made at 3d Weather Wing, Global Weather Central, Offut Air Force Base, Nebraska.

Several staff members of TRC made substantial contributions to the study. Mr. William Clink was responsible for the proposed sound-propagation evaluation model (Section II.B and Appendix C). Consultations with Mr. Norman Bowne were helpful in the diffusion aspects of the study. Mr. Marshall Atwater wrote the IBM 1620 programs used in the jet-stream verification study (Section II.D). Mr. Bernard Erickson wrote the required IBM 1620 programs and assisted in the evaluations described in Section II.E.

ABSTRACT

The predictability of wind and virtual temperature profiles from the surface to 30 km for 0- to 72-hr forecast intervals has been evaluated. Meaningful forecast verification criteria were established for each of four NASA operational problem areas affected by winds and virtual temperatures: (a) launch and flight of an aero-space vehicle, (b) propagation of sound from missile firings (both static and real), (c) diffusion of toxic fields, and (d) design of missiles. Predictions of wind and virtual temperature profiles prepared by various methods were evaluated by the criteria established for the four problem areas. It was concluded that the state of the art was deficient in several areas of profile predictions considering the user's requirements. A Technique Development Plan was designed to guide the development of new prediction techniques and to tailor existing techniques specifically to meet the National Aeronautics Space Administration/Marshall Space Flight Center operational requirements.

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I. INTRODUCTION

This report describes the results of a survey of the present state of the art for predicting wind and virtual temperature profiles, for periods up to 72 hours, from the surface to 30 km. The quality of the prediction techniques was evaluated with the primary objective of determining how well each technique satisfies various National Aeronautics & Space Administration/Marshall Space Flight Center (NASA/MSFC) operational requirements. Consultation with NASA/MSFC and The Travelers Research Center, Inc. (TRC) experts in the fields of aerospace vehicle launch and design, sound propagation, and diffusion of toxic fuels, provided the required information as to what aspects of the profile predictions are important to each operation.

Section II of this report describes the results of the evaluation of the profile prediction techniques—both the directly available profile forecasts, and those that may be derived from information at constant pressure surfaces. These results are summarized in Section III. Section IV consists of a Technique Development Plan designed to advance the state of the art of profile predictions (specifically for NASA/MSFC operations) where the evaluation has indicated it is necessary.

II. EVALUATION OF PRESENT STATE OF THE ART

It was originally planned that a large portion of the evaluation of the present state of the art for predicting wind and virtual temperature profiles would be the evaluation of a representative sample of operational forecasts prepared for three sites of interest to NASA/ MSFC operations. These sites are: Marshall Space Flight Center (MSFC), Huntsville, Alabama; Kennedy Space Flight Center (KSFC), Cape Kennedy, Florida; and Mississippi Test Operations (MTO), near Slidell, Louisiana.

A completely representative sample of operational forecasts was not available for all levels and all forecast periods of interest. This required some change in emphasis at the onset of the research.

Our survey of the state of the art of the predictability of wind and virtual temperature profiles included an investigation of forecast techniques currently being used by government agencies, both civilian and military, and airlines, and those that have been, or are in the process of being developed at the Travelers Research Center, Inc. (TRC) for various government agencies.

In the assessment of the state of the art for predicting wind and virtual temperature profiles, we considered the operational environment of the field forecaster for NASA/ MSFC operations. The "ground rules" of the operational environment are:

(a) High-speed electronic computer capability,

(b) Limited manpower, i.e., two meteorologists plus two computer operators, and

(c) Special "on-site" observational capabilities.

In this operational environment, the field forecaster has access to three classes of information:

(a) Centrally-prepared analyses and prognoses,

(b) Observational data from the conventional meteorological networks, and

(c) Special "on-site" observational capability, i.e., the ability to make frequent rawinsonde runs.

To satisfy user requirements, the field forecaster has to perform some "tailoring" of centrally-prepared products. Considering the limited-manpower ground rule, it appeared that a logical beginning would be to establish the adequacy of the centrally-prepared analyses and prognoses to meet user requirements of interest in this study. A result of this was the determination of the magnitude of the "tailoring" task facing the field forecaster. Existing automated prediction techniques, which are in the latter stages of development and which were developed primarily to satisfy other user requirements, were evaluated because of their possible application in advancing the state of the art in wind and virtual temperature profile prediction.

A list of prediction techniques that were evaluated follows. Some of these techniques do not result in direct profile forecasts, but can be used to derive a portion or portions of the wind and/or temperature profile. The centrally-prepared prognoses are indicated.

(a) National Meteorological Center winds aloft and temperature forecasts (0.9 km to 12.5 km, up to 24 hours, centrally prepared) [see Section IIA];

(b) NASA/MSFC operational forecasts for sound profile forecasts [see Section IIB];

(c) Planetary boundary-layer physical prediction models [see Section IIC];

(d) Jet-stream prediction techniques [see Section IID]

(1) 3-level baroclinic numerical model (centrally prepared)

(2) 6-level baroclinic numerical model (centrally prepared)

(3) Level of maximum wind physical-statistical modeling technique

(4) Subjective, Air Force wind profile forecasts for Cape Kennedy in support of vehicle launch;

(e) Physical-statistical synoptic vertical extrapolation technique [see Section IIE].

The objectives of the evaluations reported in the following sections are to:

(a) establish the adequacy of centrally-prepared products for meeting the operational requirements of the test sites; this in turn gives an indication of the magnitude of the prediction problem facing the field forecaster;

(b) help delineate problem areas of operational and simulated operational forecasts, and;

(c) assess the potential of new forecast techniques as they apply directly to the operational requirements considered in this study.

Subsequent sections describe the evaluation of each of the forecast types, and of the aspects of the profiles considered important in the application of the predictions by NASA/MSFC, i.e., sound propagation, vehicle launch and design, and diffusion of toxic fuels.

A. National Meteorological Center Winds-aloft Forecasts

Forecasts of winds aloft (and temperature) (FD's) have been prepared by the National Meteorological Center (NMC) for transmission on Service A teletype since August 5, 1964, in support of aviation meteorology. The forecasts are for seven levels* to 25,000 feet (~ 8 km) for selected stations in the U.S. In June 1965, three more levels were added to the forecasts (30-, 34-, and 39-thousand feet, ~ 10, 11, and 12.5 km, respectively). The forecasts for these three levels are transmitted on the Automatic Data Interchange System (ADIS) teletype circuit. The three locations of interest to NASA/MSFC space flight operations are not among those stations for which FD's are prepared, but the FD Program has the capability to generate forecasts for any location.

The FD's transmitted on Service A and ADIS teletype circuits are specified to be valid for a 6-hr period (e.g., 6—12-, 12—18-, or 18—24-hr forecasts). They are actually prepared for the midpoint of the 6-hr periods (i.e., 9, 15, and 21 hours after initial data time) from the output of NMC's currently operational numerical model, a 3-level baroclinic model. These forecasts are considered "representative of the period within three hours on either side of the forecast time" [1]. One disadvantage of these forecasts is that they are not transmitted until six hours after the initial time; thus, the 6—12-hr forecast is, as far as the user is concerned, only a 0—6-hr forecast.

In a description of the FD Program [1], the authors state that "complaints have been received from the field on the poor quality of the low-level wind and temperature portions of the forecast." The "Note" goes on to describe how the FD's are prepared

*The forecast levels are 3-, 5-, 7-, 10-, 15-, 20- and 25-thousand feet (temperature forecasts are not made for 3- and 7-thousand feet).

and what the sources of error are, and then presents some verifications of the forecasts. A brief summary of the content of the "Note" is given in Appendix A.

Verification by the National Meteorological Center

National Meteorological Center wind verifications were presented in "Note to Forecasters" [1], for only two levels—5,000 and 20,000 ft. These are the levels that are closest to two of three levels in the model (850 and 500 mb, respectively).

Consultation with NMC personnel resulted in our obtaining more detailed verifications from NMC of winds for 12- and 24-hr forecasts for 34 U.S. radiosonde observation (RAOB) stations (combined and individually). The verifications were performed during a 25-day period from April 5 to April 30, 1965.

In general, the verifications indicated that greater than 75% of the errors for all levels are in the 3—8 m sec^{-1} range, with a highest average observed speed for any level of 27 m sec^{-1}. Tables B-1, B-2, and B-3 in Appendix B present the detailed statistics for three RAOB stations nearest the NASA/MSFC locations of interest.

Examination of the NMC verifications of the FD's reveals rather large vector errors, in terms of percent, in the lower levels (at and below 3.3 km), where:

$$\%\ \text{error} = \left| \frac{\text{fcst - obs}}{\text{obs}} \right| \times 100$$

At the higher levels (~ 4 to 8 km) the percent error is somewhat lower (although the vector error is nearly the same). It may be stated that the percent vector errors of the winds-aloft forecasts are relatively high for the sample of forecasts that were verified.

The only temperature forecasts verified by NMC were in one special verification run for 12-hr temperature forecasts for one station (New York City, JFK), for a 20-day period, and for three levels. The levels and the root-mean-square errors (rms errors) for each level are as follows:

1.5 km—4.7°C

3.3 km—2.2°C

6.5 km—1.4°C

Verification by The Travelers Research Center, Inc.

Because the verifications carried out by NMC were in the form of the usual error statistics, and not with respect to the effect errors in the profile forecasts would have on the sound profile or on the flight of an aerospace vehicle, a special collection of FD's was made from data of September 1965. The purpose of obtaining this special collection was to verify the forecasts relative to their usefulness in meeting NASA/MSFC operational requirements.

Two stations in the southeastern United States were selected as being representative of the three NASA/MSFC sites of interest (Nashville, Tennessee, and; Miami, Florida) and forecasts for these stations were verified. (Table B-4 in Appendix B of this report presents the detailed statistics.) The following discussion interprets the verification statistics and limitations of the FD's as they satisfy the NASA/MSFC requirements.

Sound Propagation

A sample of FD's, detailed observed soundings, and observed values (for the time of the forecast) at FD levels only was sent to MSFC in Huntsville. All except the detailed observed profiles were run through MSFC's sound-ray tracing program and the results were evaluated. Figure 1 (a—f) is a typical example of a forecast and observed pair for six representative directions.

The reasons for the rather poor sound profile and acoustic returns specified by the FD's are due to two major factors:

(a) the insufficient vertical definition, particularly in the lower 5 km (e.g., temperature forecasts are for 1.5, 3.3, and 4.8 km), and

(b) the relatively large errors of the forecasts themselves; these are due to the errors inherent in the procedure that generates the forecasts (see Appendix A for details).

It can be stated with a fair degree of confidence that the sound profile and acoustic returns estimated from the detailed observed soundings would differ from the estimates based only on information at FD levels (e.g., temperature forecasts are for 1.5, 3.3, and 4.8 km). NASA/MSFC and TRC sound propagation experts agreed that using only the levels of the FD's gives insufficient sound profile definition to satisfy the requirement for accurate and detailed sound-speed profiles.

Vehicle Launch and Design

There has been a considerable amount of research devoted to the effect of the wind speed and shears on the behavior of a vertically-rising vehicle. Much of this research has been described and reported in the literature [19, 27, 45]. From these sources, and from consultation with NASA/MSFC personnel, there is general agreement that the effects of the wind speed and vertical shears attain maximum importance in the region where the jet stream is located. In this region, excessively-high horizontal wind speeds and vertical wind shears may be encountered. The major jet-stream types are the polar jet and the subtropical jet. The polar jet is rarely observed over Cape Kennedy, but the subtropical jet is frequently located over Cape Kennedy in the winter season. The height at which the subtropical jet is located is usually between 12 and 16 km, and the highest level of the FD's is about 13 km. Thus, these forecasts are not adequate, in most cases, for completely describing the wind profile in the vicinity of (and particularly above) the subtropical jet.

Table 1 presents the wind and temperature error statistics for 12- and 24-hr FD's at the three highest levels of the forecast. It is seen from the average observed wind speed that the wind flow was relatively weak for this data sample, with the highest average speed of 18 m sec^{-1} at approximately the 13 km level at Nashville. The rms vector error of the wind was 11 m sec^{-1} for this level; this may be considered rather high for the average observed wind speed. The magnitude of the error would probably be greater during a period of strong wind speeds.

Considering the nature of the FD procedure and its limitations, it is concluded that the FD technique would not provide a satisfactory solution for meeting NASA/MSFC requirements for profile predictions necessary for vehicle launch operations.

Diffusion

Because the present diffusion model in use at Cape Kennedy requires input parameters from the lower 20 meters of the atmosphere, the FD's are not applicable to diffusion prediction.

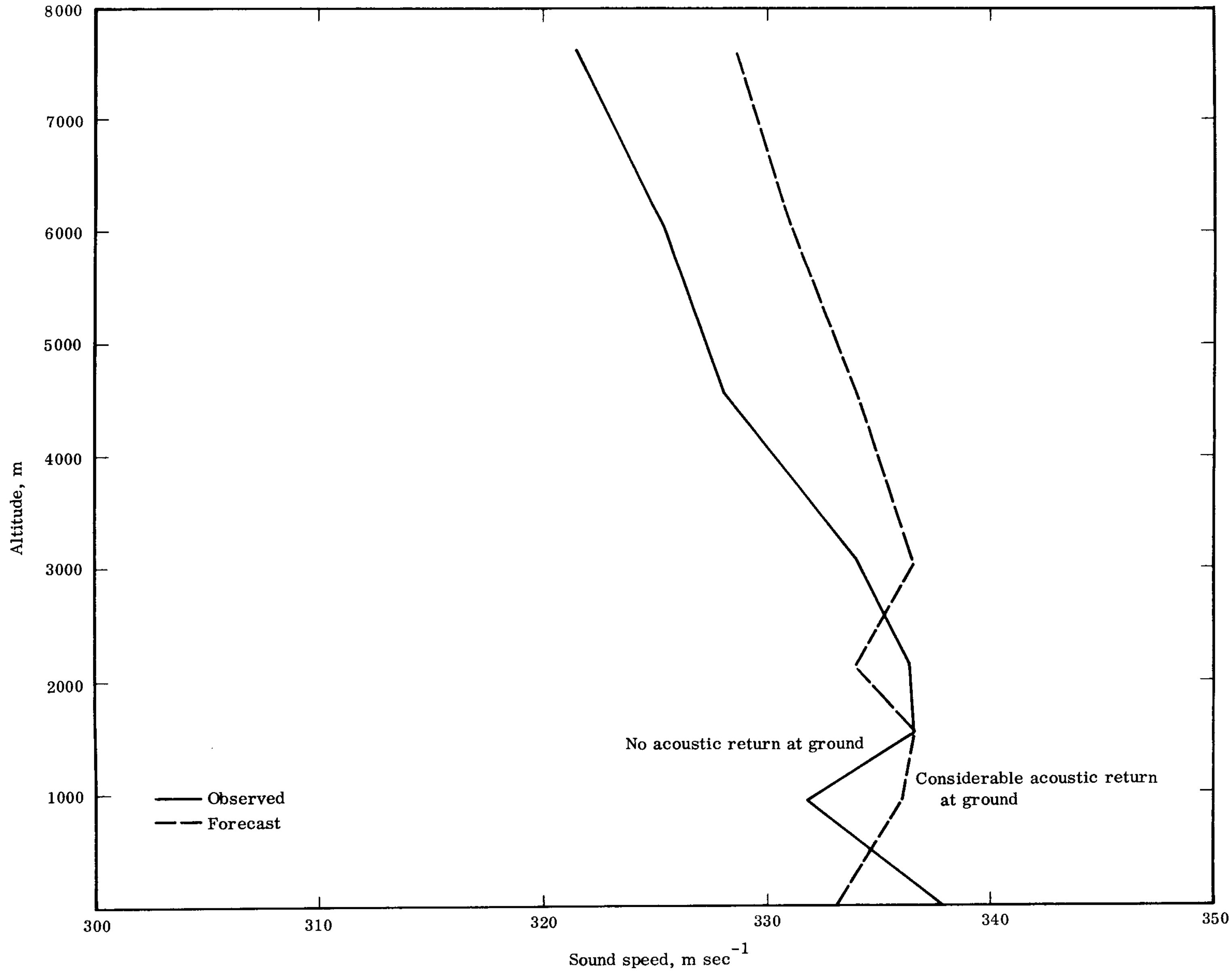

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (a) α = 50°.

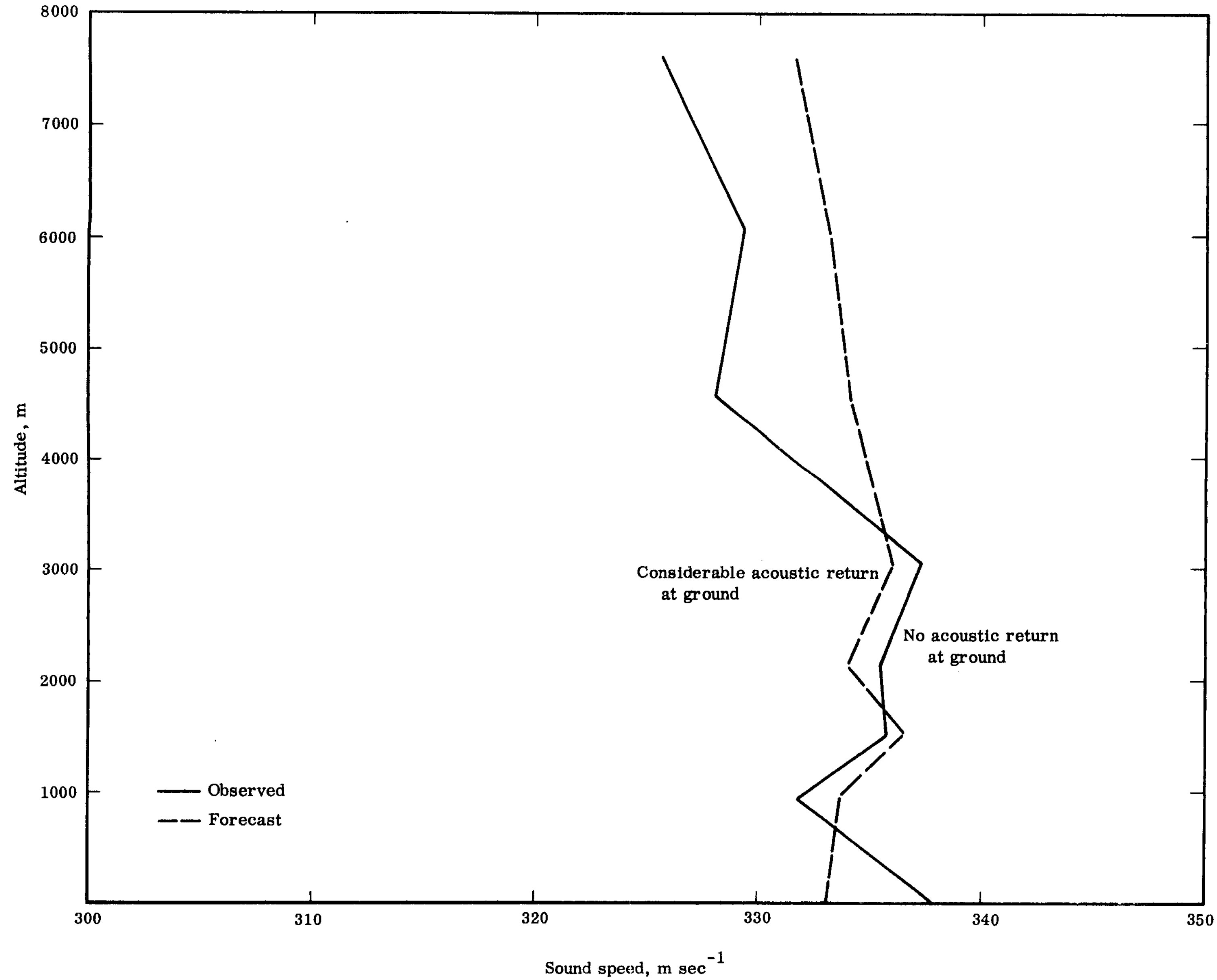

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (b) α = 110°.

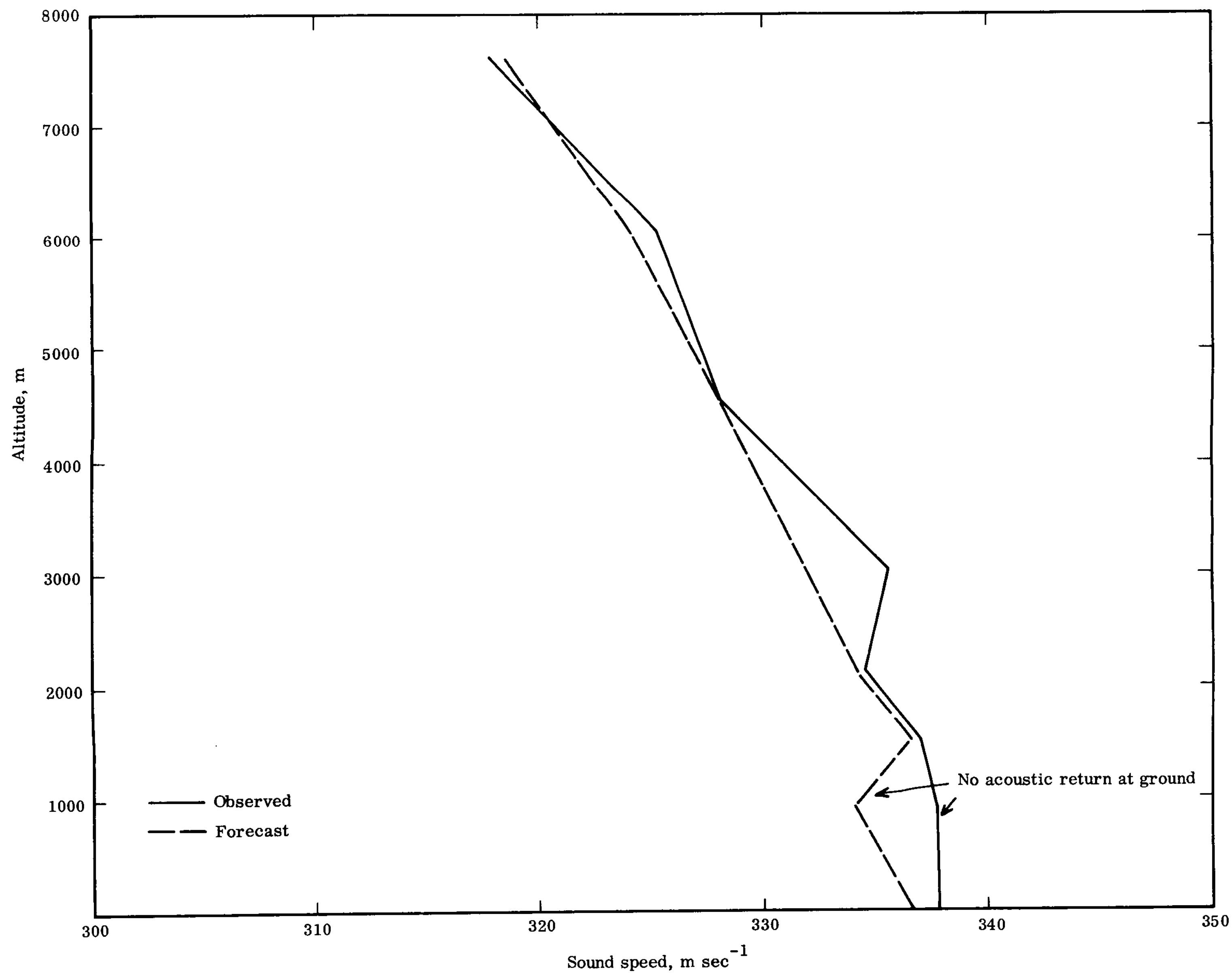

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (c) α = 170°.

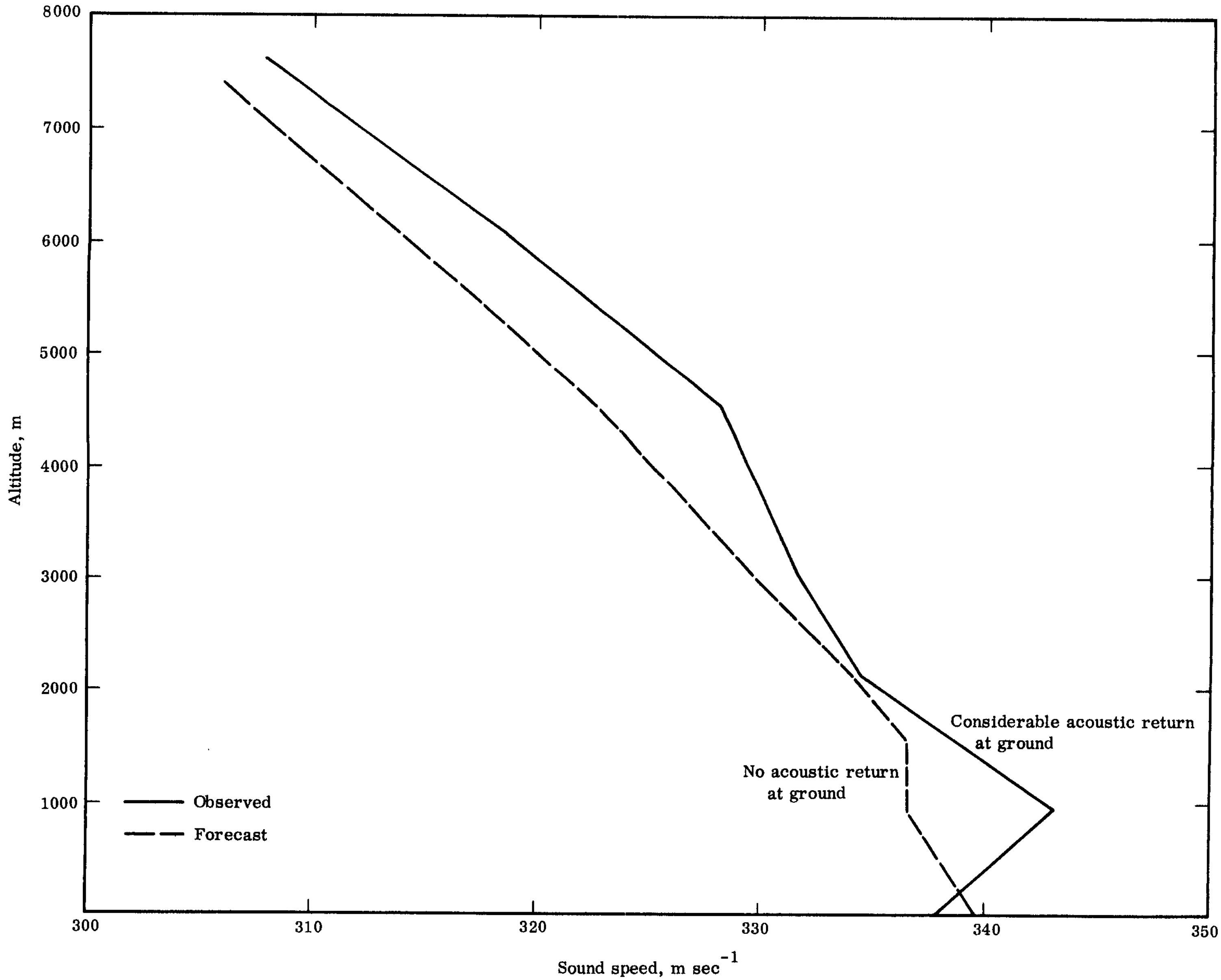

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (d) α = 220°.

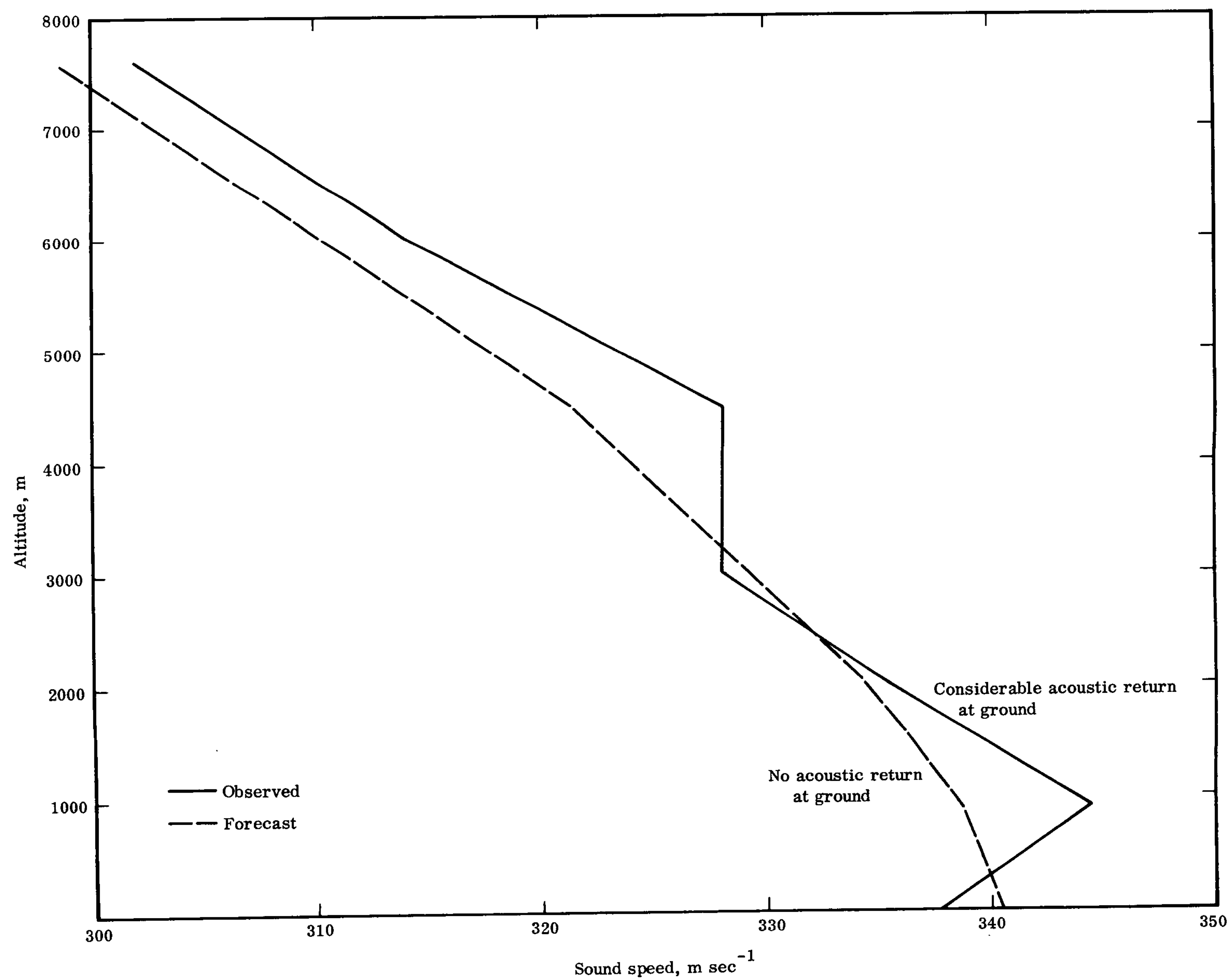

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (e) α = 270°.

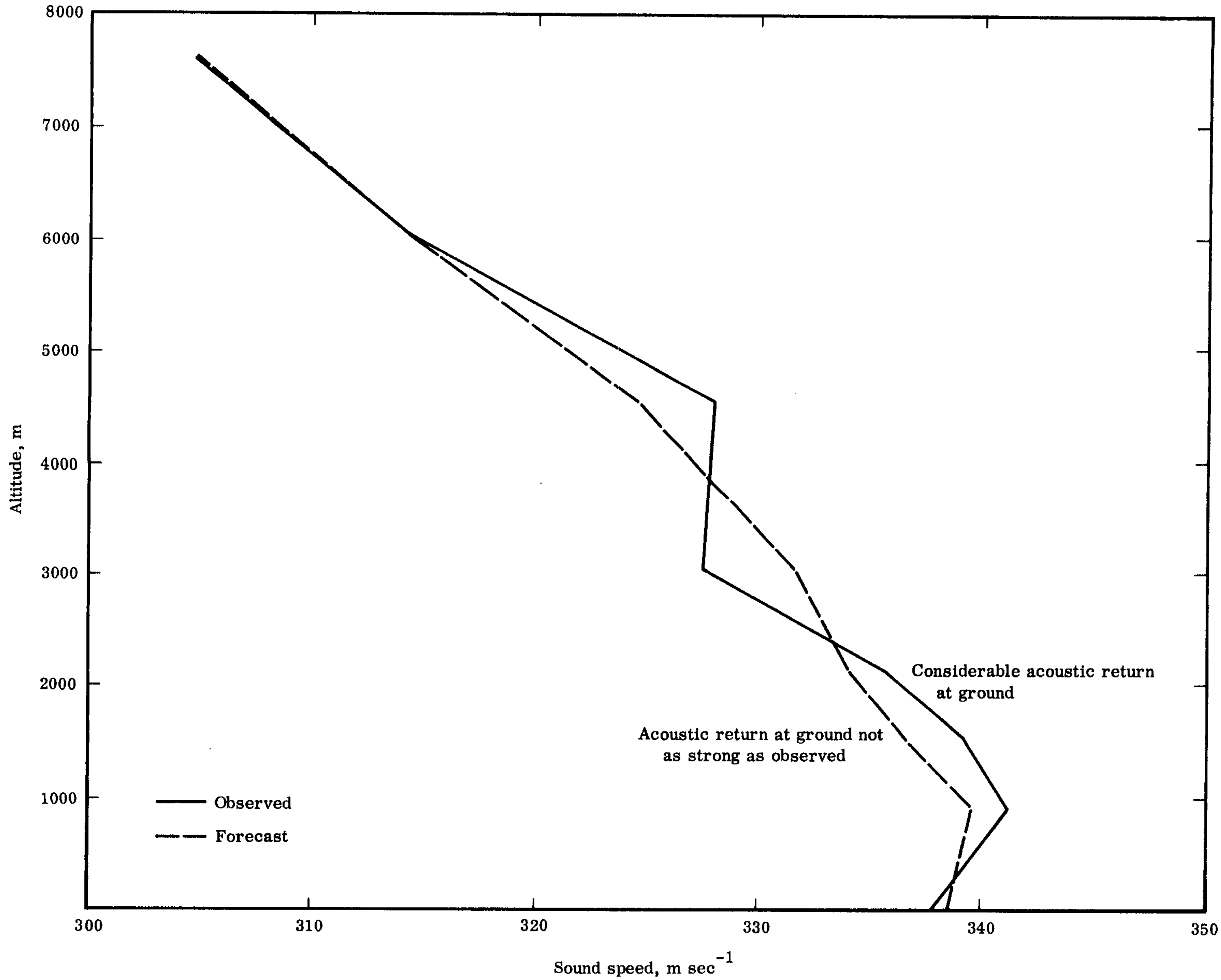

Fig. 1. Observed and FD Sound Speed Profiles; Nashville; 1200 Z, 27 September 1965. (f) α = 320°.

TABLE 1
ROOT-MEAN-SQUARE ERROR OF WINDS-ALOFT AND TEMPERATURE FORECASTS

(September data, 60 cases)

Forecast period (hr)	Altitude (m & ft)	Nashville					Miami				
		Parameter					Parameter				
		u*	v*	$\vec{V}$*	Avg. speed†	T‡	u*	v*	$\vec{V}$*	Avg. speed†	T‡
12	9843 (30,000)	3.9	5.3	6.6	16.0	1.5	3.4	5.4	6.5	9.5	1.3
	11062 (34,000)	5.5	7.0	9.2	19.0	1.7	6.7	8.5	11.0	11.0	1.3
	12586 (39,000)	5.0	8.4	10.0	20.5	2.4	5.4	8.0	9.9	13.6	1.5
24	9843 (30,000)	5.7	6.9	9.2	15.6	1.4	5.0	6.7	8.5	8.8	1.7
	11062 (34,000)	6.3	8.7	10.8	18.0	0.8	5.8	9.8	11.5	10.9	2.0
	12582 (39,000)	6.1	9.3	11.4	19.7	1.5	8.0	11.0	14.0	13.9	2.5

*m sec^{-1}
†Observed
‡°C

B. NASA/MSFC Operational Forecasts

A sample of 47 6-hr wind and virtual temperature profile forecasts prepared by NASA/MSFC personnel was made available to us along with the corresponding observed data. To make a comparative assessment of acoustic return from these forecast and observed profiles, a simple geometrically-derived model was formulated. The Simplified Acoustic-ray Tracing (SART) Model is designed to represent a "transfer function" relating regions of anomalous intensification with the causative meteorological variables. It is used to quantify a meteorological profile, producing a number or numbers which may be used to compare associated profiles (e.g., forecast vs measured), but it is not intended to be used as an operational forecasting model. It is a straightforward ray-tracing model and, basically, is similar to models others have used, e.g., [43]. The details of the model are described in Appendix C. Briefly, the model has the following characteristics:

(a) It provides a number or a few numbers which quantify or typify the effect of a vertical profile of meteorological variables on associated anomalous aspects of the propagation of sound from a surface source to a surface receiver. Theoretical accuracy may be compromised where effects are small compared to verifications common to meteorological information, or where occurrences are rare. The model is not specific to any one source or situation, but provides information in a form and range easily assimilable by common users.

(b) It gives no attention to non-critical profile regions and does not trace the path of sound rays in order to determine range and intensity. The assumption is made that all refraction takes place at the top of an associated critical segment of the profile. Other simplifications include the truncation of trigonometric-function series expansions.

(c) Its output is in the form of ranges, energy fluxes returned by the profile segment in an azimuth region of one radian, and maximum sound intensities in the form of decibel sound pressure levels (SPL's). The latter two are approximately normalized for a source strength of one megawatt.

Inspection of a number of meteorological profiles and the output of the SART Model indicated a distinct division of sound intensity into two regions. Anomalous propagation by surface-based critical regions was far more prevalent than by critical regions aloft, and the characteristics of the two were also different. Other than this, there was no other obvious divisions, such as into regions with distinctive profile characteristics. A grouping of profiles into five classes, as has been suggested in the literature [43], did not seem to have any advantage. Instead, the assessment of a profile at two points, next to the surface and at the first major critical area aloft, seemed to be best for a semi-objective result.

With the normalized sound-pressure-level (SPL) values obtained from the SART Model, a procedure was formulated in which differences in SPL values between two associated profiles would be plotted against the SPL value of one of the profiles (e.g., the forecast profile). This has been done for 47 pairs of profiles (6-hr MSFC forecasts, and observations from MSFC, for dates between October 1964 and September 1965). The results, plotted separately for the two proposed classifications, are shown in Table 2. In these few cases, serious errors occur because the sound intensity would reach objectionable decibel levels, but would not be forecast to do so. These objectionable decibel levels are caused by definite atmospheric intensification of sound at the surface (and not by an acute focus).

It should be pointed out that these 6-hr forecasts may not be a completely representative sample of forecasts covering all synoptic situations.

Although we did not have 24-hr forecast profiles for which we could assess the acoustic return, it is expected that the forecast accuracy would be less than for the 6-hr forecasts, considering the normal decrease in confidence factors with longer range forecasts.

C. Planetary Boundary Layer Prediction

As the atmosphere flows over the earth's surface, it is subjected to a variety of forces—expressed in the Navier Stokes form of the momentum equations, including the additional Coriolis effect arising from the rotation of the earth. In addition to these forces which act directly on the momentum of the air, the earth's surface can influence the structure of the air by acting as a source (or sink) of both sensible and

TABLE 2
CLASSIFICATION OF ACOUSTIC COMPARISONS
BETWEEN 47 PAIRS OF METEOROLOGICAL PROFILES

(a) Acoustic returns from surface-based regions

		Forecast decibel level			
		< 80	80—90	91—100	> 100
Measured fcst error (db) (obs minus forecast)	> 25	2			
	16—25	2			
	6—15	3	3	3	
	-5—5	4	4	14	1
	-15— -6		2	3	
	< -15		2	4	

(b) Acoustic returns from regions aloft

		Forecast decibel level			
		> 80	80—90	91—100	> 100
Measured fcst error (db) (obs minus forecast)	> 25	1			
	16—25	1			
	6—15	2	1	2	2
	-5—5	23	6	2	3
	-15— -6		3		
	< -15			1	

latent heat. Beyond the fundamental complexity of the physical interaction indicated above, one must note that the characteristics of the earth's surface as a source, or sink, of momentum and heat depend significantly upon the structure of the air. For example, the amount of heat available at the earth's surface depends upon the transmissivity of solar radiation through the air.

In the past, it was useful to study the characteristics of idealized, or model, atmospheres in order to understand the behavior of the real atmosphere. This approach was initiated near the end of the 19th century, but it was only after the introduction of the electronic-digital computer in about 1950 that it became possible to examine the predictive utility of these theoretical models.

The success achieved in predicting the large-scale motion of the atmosphere in the mid-troposphere by the simple barotropic model led to the investigation of the utility of more complex models for predicting the large-scale thermodynamic properties of the air. These baroclinic models have recently been perfected to the point that the routine forecasts of the National Meteorological Center (NMC) are based upon Cressman's 3-level baroclinic model [4]. Current research and development at NMC is directed toward the implementation of a 7-layer model in which a rudimentary treatment of the boundary layer is incorporated.

The first studies of the structure of the planetary boundary layer that utilized a physical-numerical model were conducted by Estoque [8, 9], Fisher [10], and Fisher and Caplan [11]. During the past three years, research directed toward the development of two operationally-useful boundary-layer models has been conducted at TRC. These two models have been designed to function with distinct sources of observational data. In one case [31, 32, 33], the routine data are to be augmented by observations made using meteorologically instrumented towers, slow-rise radiosondes, and other special equipment located in a subsynoptic-scale network. In the other case [14, 15], only routine observations are required as a data source.

The models indicated above are capable of further development, but we decided to examine forecasts made with currently available versions in order to assess the models' contributions to the present state of the art in boundary-layer prediction.

The sub-synoptic-scale* model developed by Pandolfo, et al. [33], for the U.S. Weather Bureau was designed to permit short-period (up to six hours) forecasts of the vertical distribution of wind, temperature, and humidity at the center of a sub-synoptic-scale observational network. Most of the numerical experiments conducted with this model were performed using data observed during the Great Plains field program [24], and comprise the prediction of the temporal variation of the boundary-layer structure above a fixed point.

In Fig. 2 (a—d), we present the observed and predicted vertical distributions of the calm-environment sound speed and the horizontal wind components at 2-hr intervals for a morning case: 0835—1435 CST, 31 August 1953.

The initial data, Fig. 2 (a), show a nearly isothermal stratification below 800 m as indicated by the constant value of calm-environment sound speed. The horizontal wind-speed profiles show the presence of a low-level jet at 400 m. It is significant that this wind maximum could be solely responsible for the return of a sound wave. Consequently, it is important that the prediction model be capable of forecasting the development and dissipation of such wind maxima. However, there is considerable evidence that the low-level jet is frequently a nocturnal phenomenon and for this reason is not often important in daylight operations [20, 35].

The accuracy of the predictions displayed in the remaining parts of Fig. 2 is evident.

The small forecast errors would not significantly affect the accuracy of the predicted sound propagation because the vertical gradients are very accurately predicted. For the purpose of predicting diffusion characteristics, the error noted in the predicted wind speed (about 4 m sec^{-1} at 100 m) may be significant, but the static-stability profile in the lower twenty meters is predicted very well.

Figure 3 presents a night-time forecast from 2035 to 0235 CST, 8—9 August 1953. In this case, we witness the development of a strong thermal inversion and of a low-level jet. Both aspects of the observed air structure are predicted by the model with considerable accuracy, especially when one emphasizes the vertical gradients in verification.

*The sub-synoptic-scale network has characteristic spacing of ~ 10 miles between instrumented observation sites (synoptic-scale spacing is ~ 100 miles).

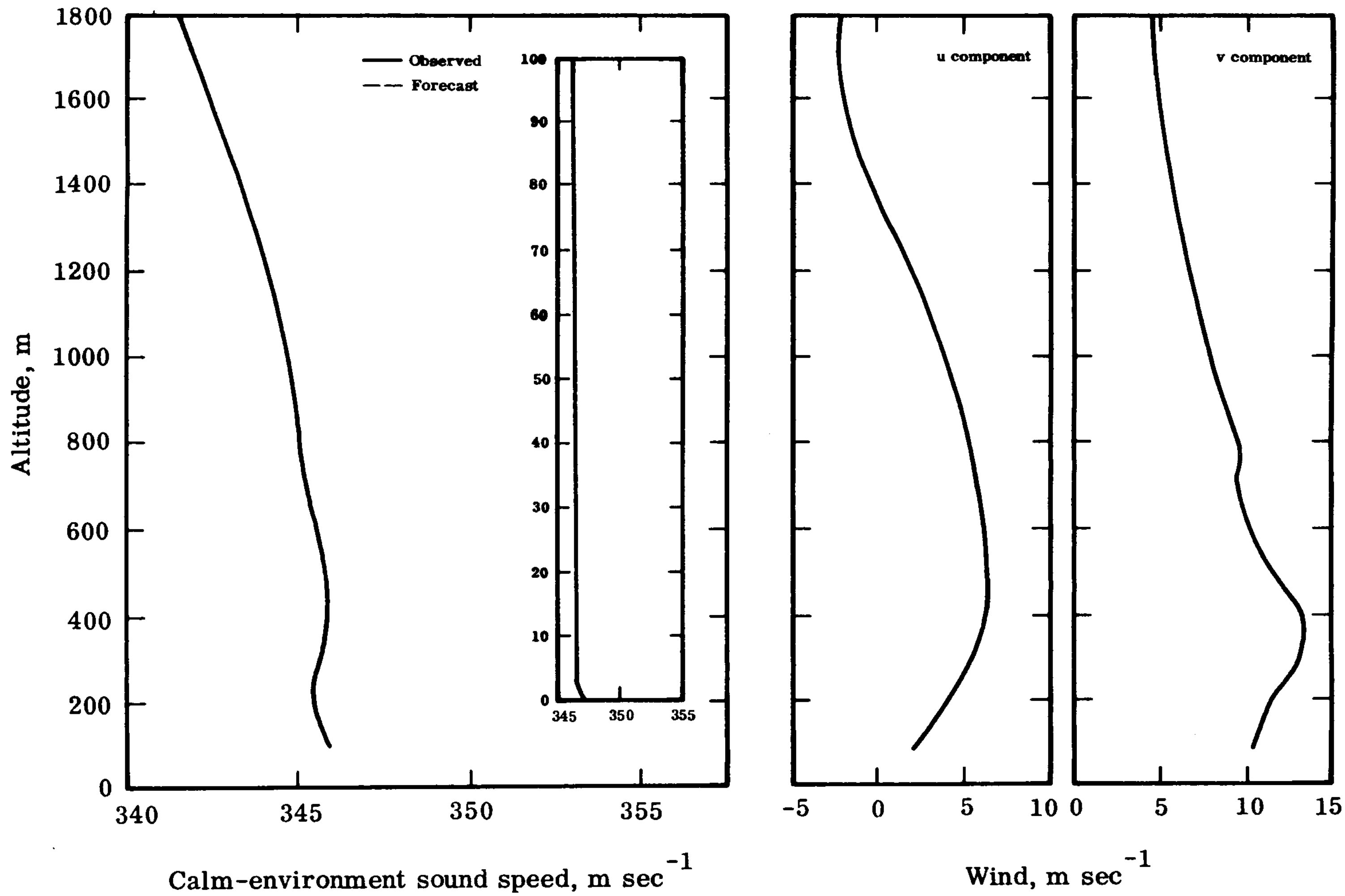

Fig. 2. Calm-environment sound speed and wind components (Great Plains Data): 31 August 1953. (a) Initial condition: 0835 CST.

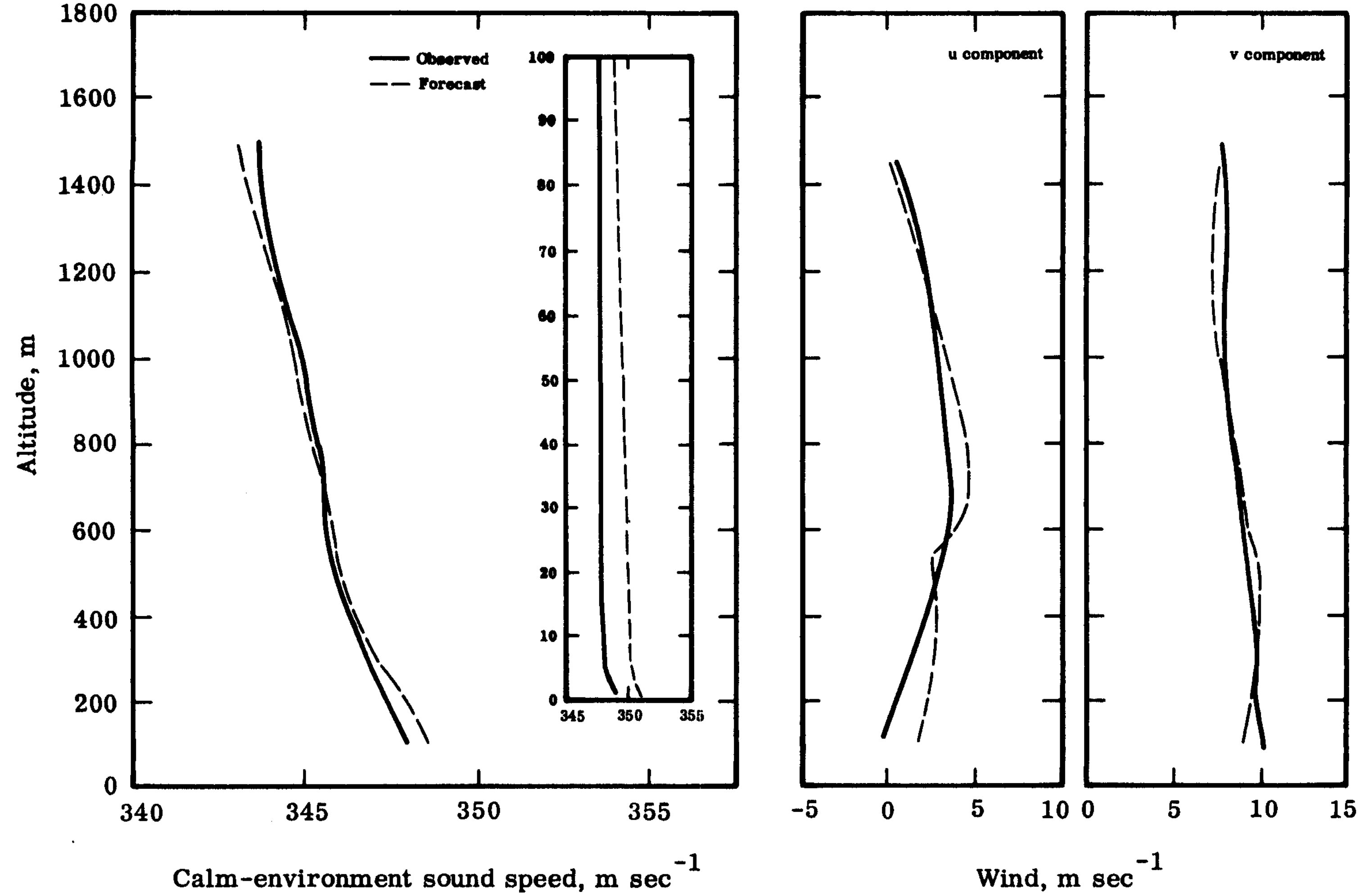

Fig. 2. Calm-environment sound speed and wind components (Great Plains Data): 31 August 1953. (b) Observed and 2-hr forecast: 1035 CST.

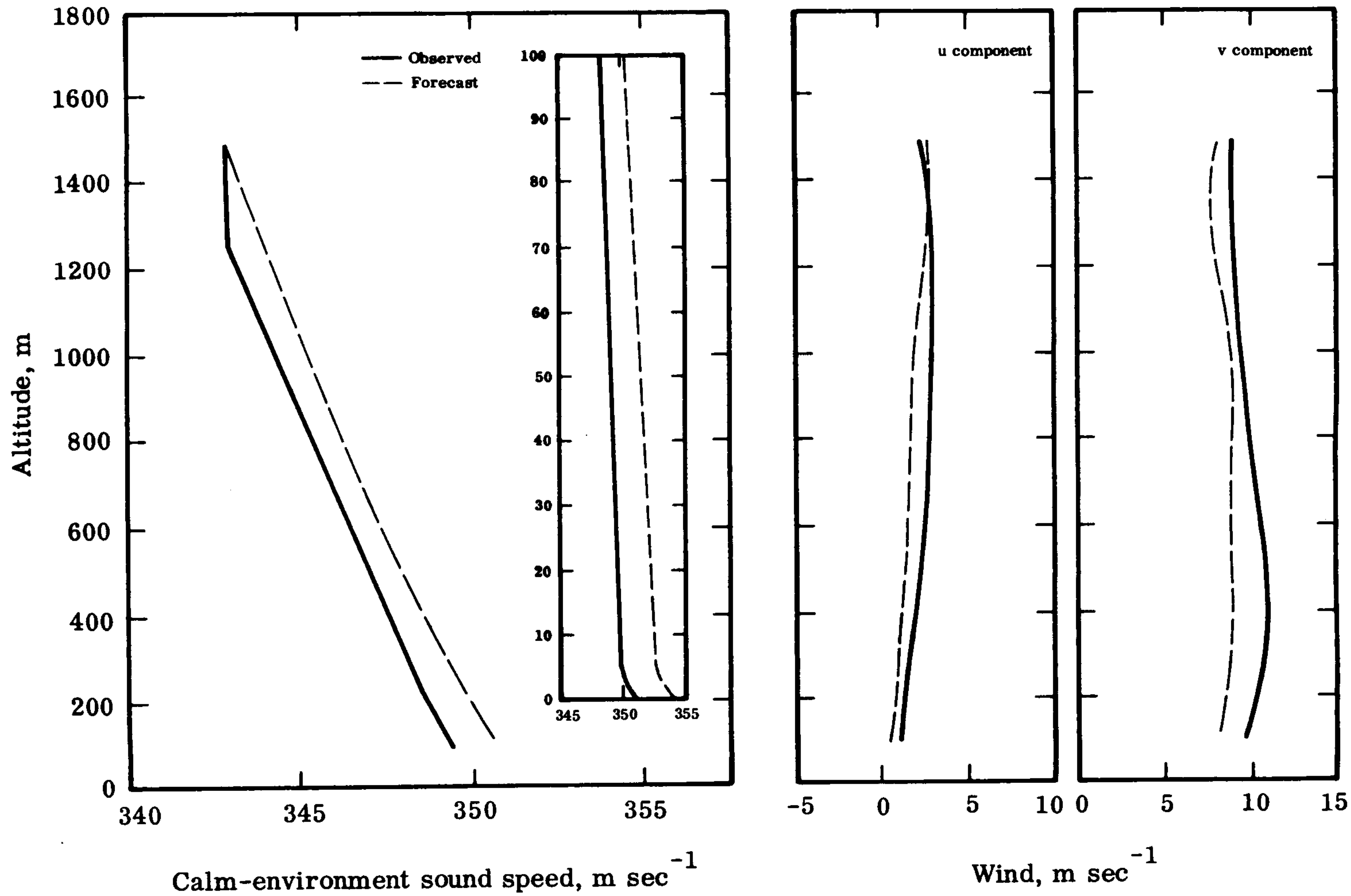

Fig. 2. Calm-environment sound speed and wind components (Great Plains Data): 31 August 1953. (c) Observed and 4-hr forecast: 1235 CST.

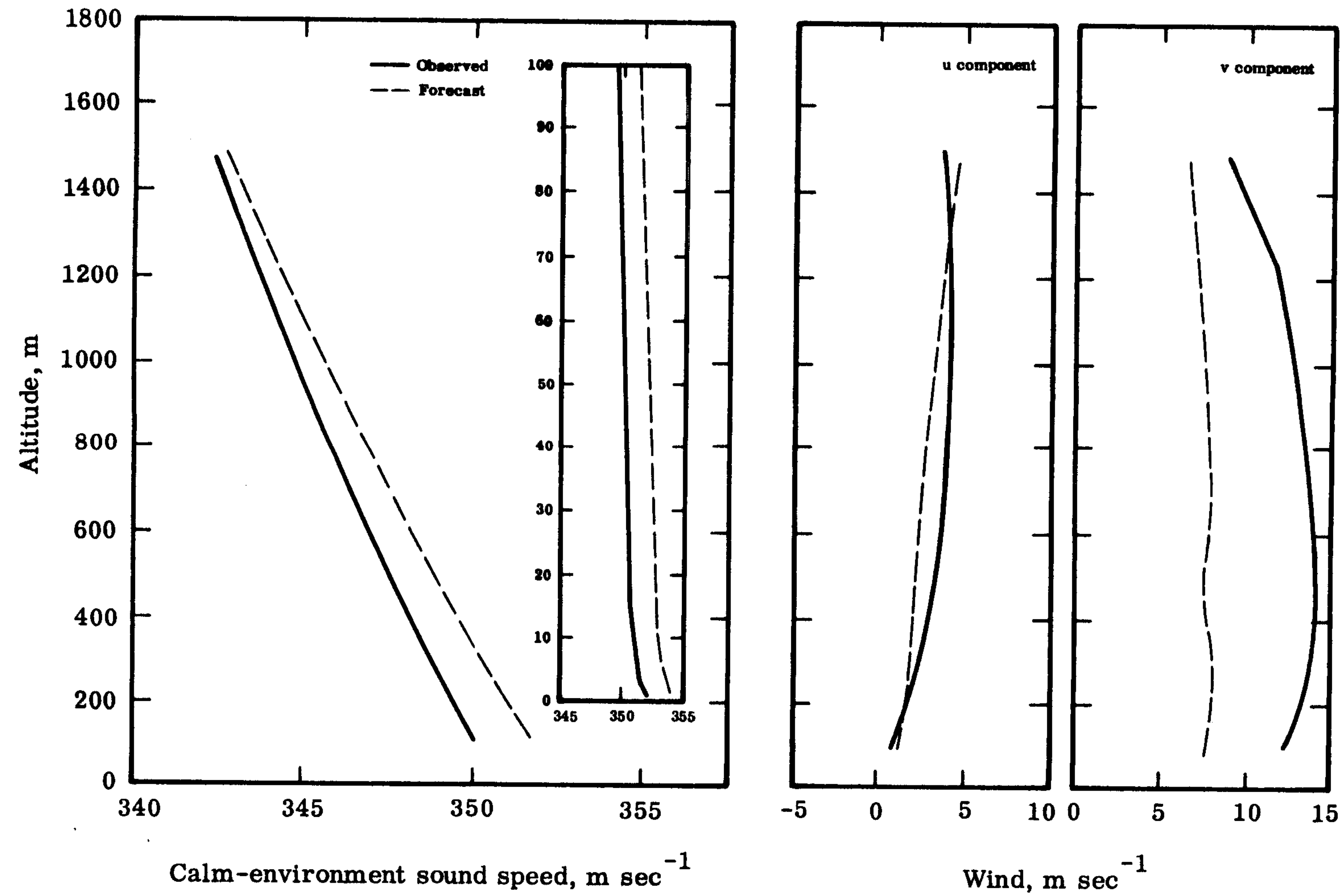

Fig. 2. Calm-environment sound speed and wind components (Great Plains Data): 31 August 1953. (d) Observed and 6-hr forecast: 1435 CST.

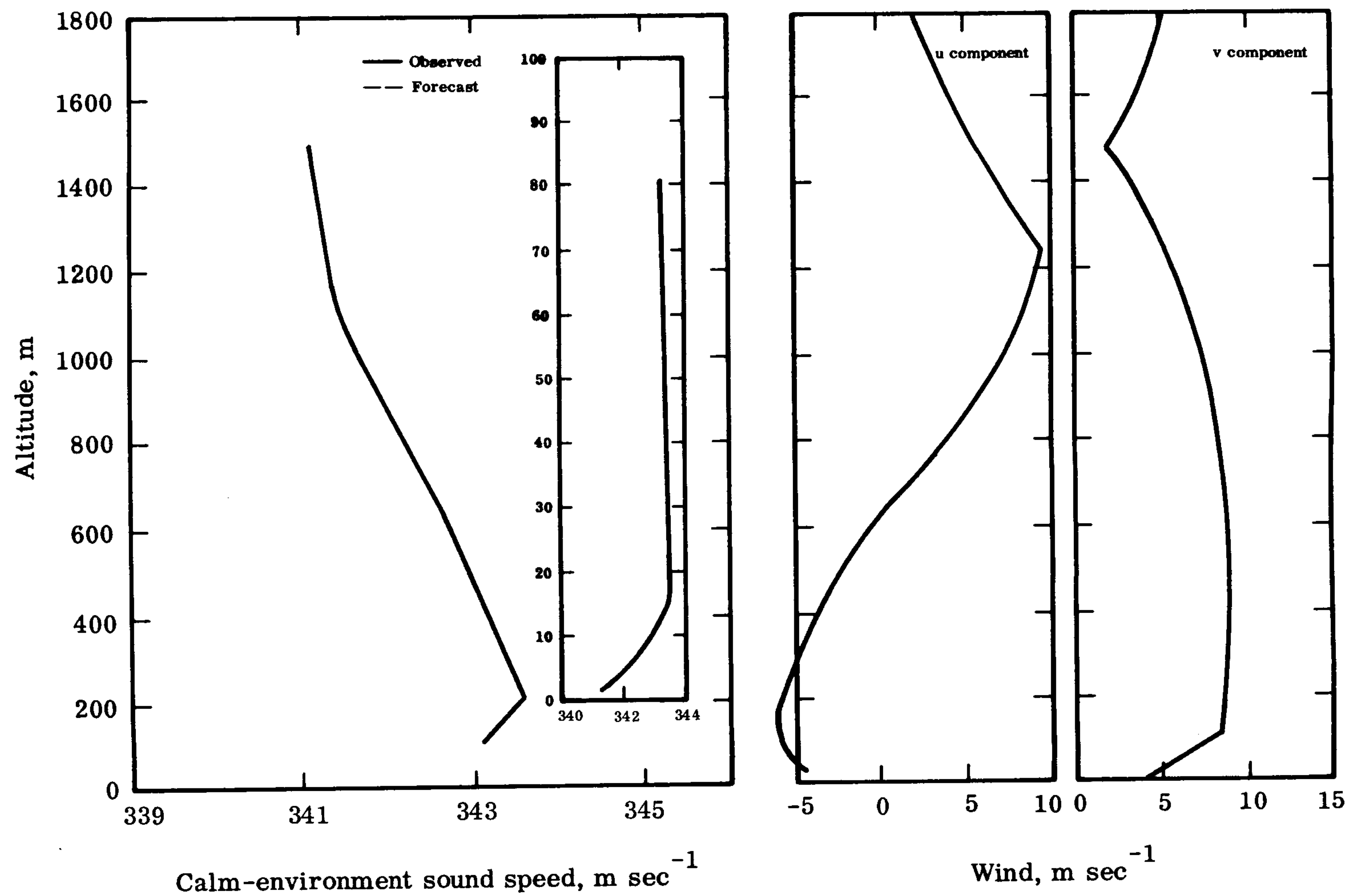

Fig. 3. Calm-environment sound speed and wind components: 8—9 August 1953. (a) Initial conditions: 2035 CST.

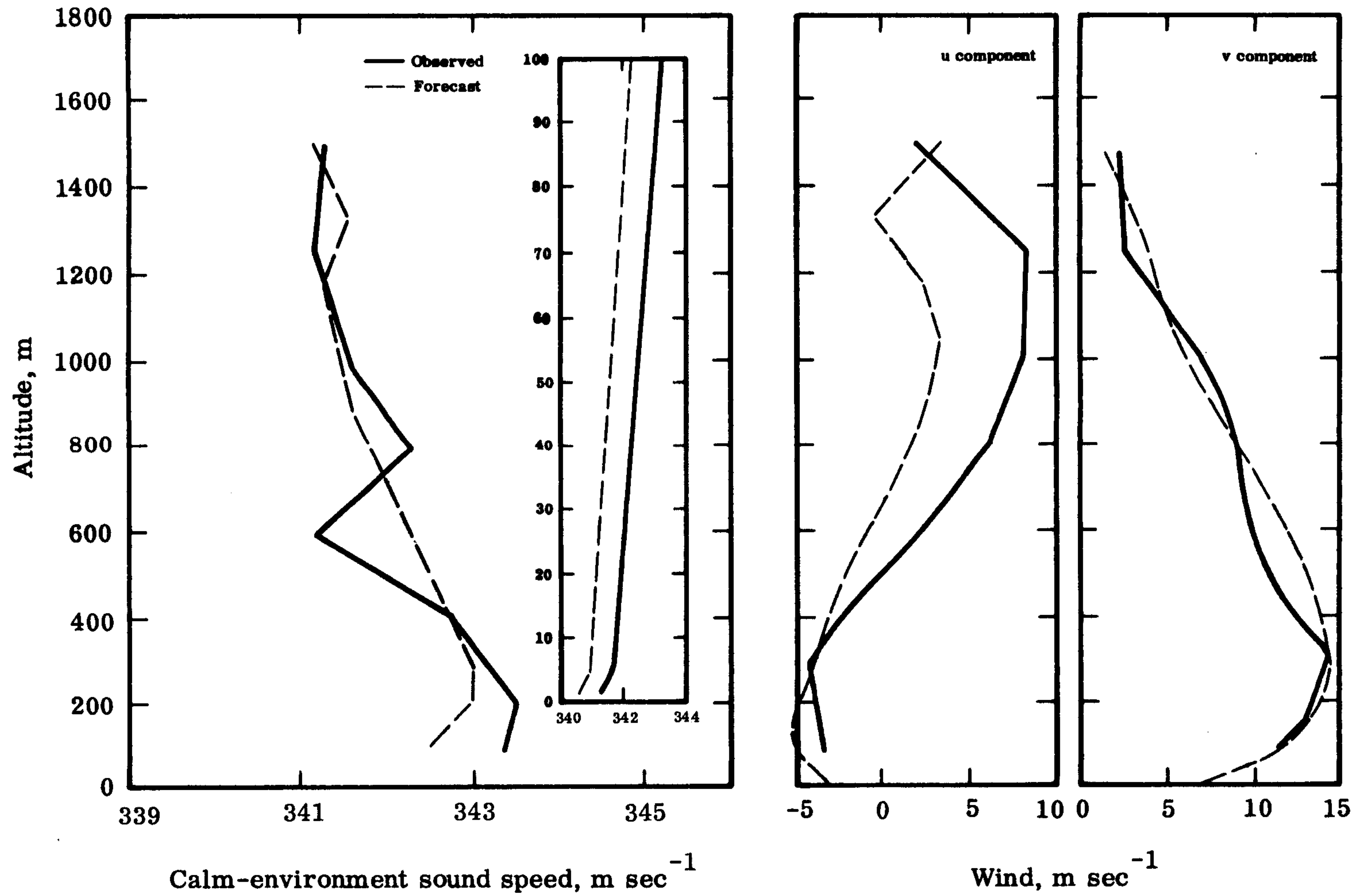

Fig. 3. Calm-environment sound speed and wind components: 8—9 August 1953. (b) Observed and 2-hr forecast: 2235 CST.

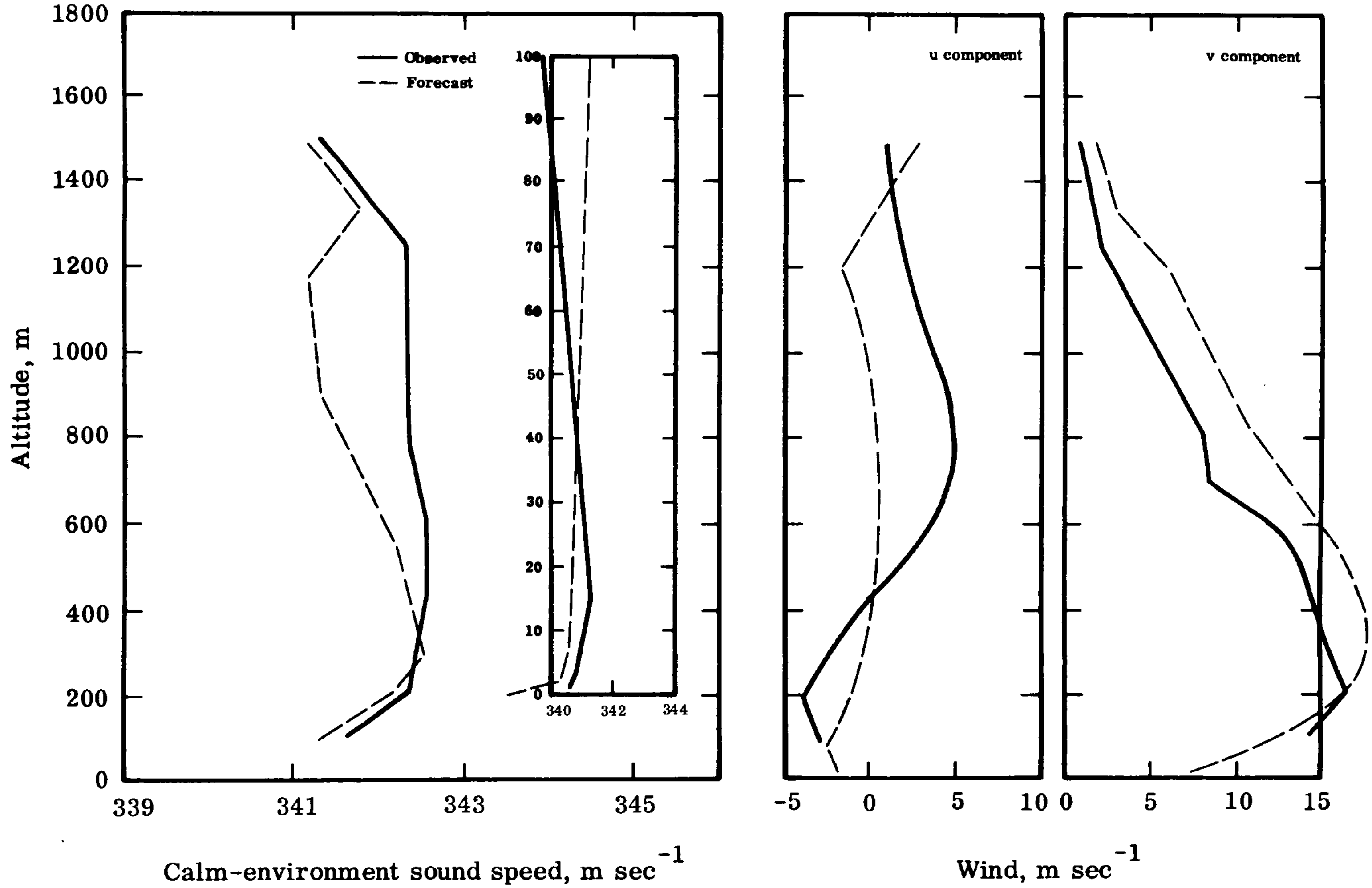

Fig. 3. Calm-environment sound speed and wind components: 8—9 August 1953. (c) Observed and 4-hr forecast: 0035 CST.

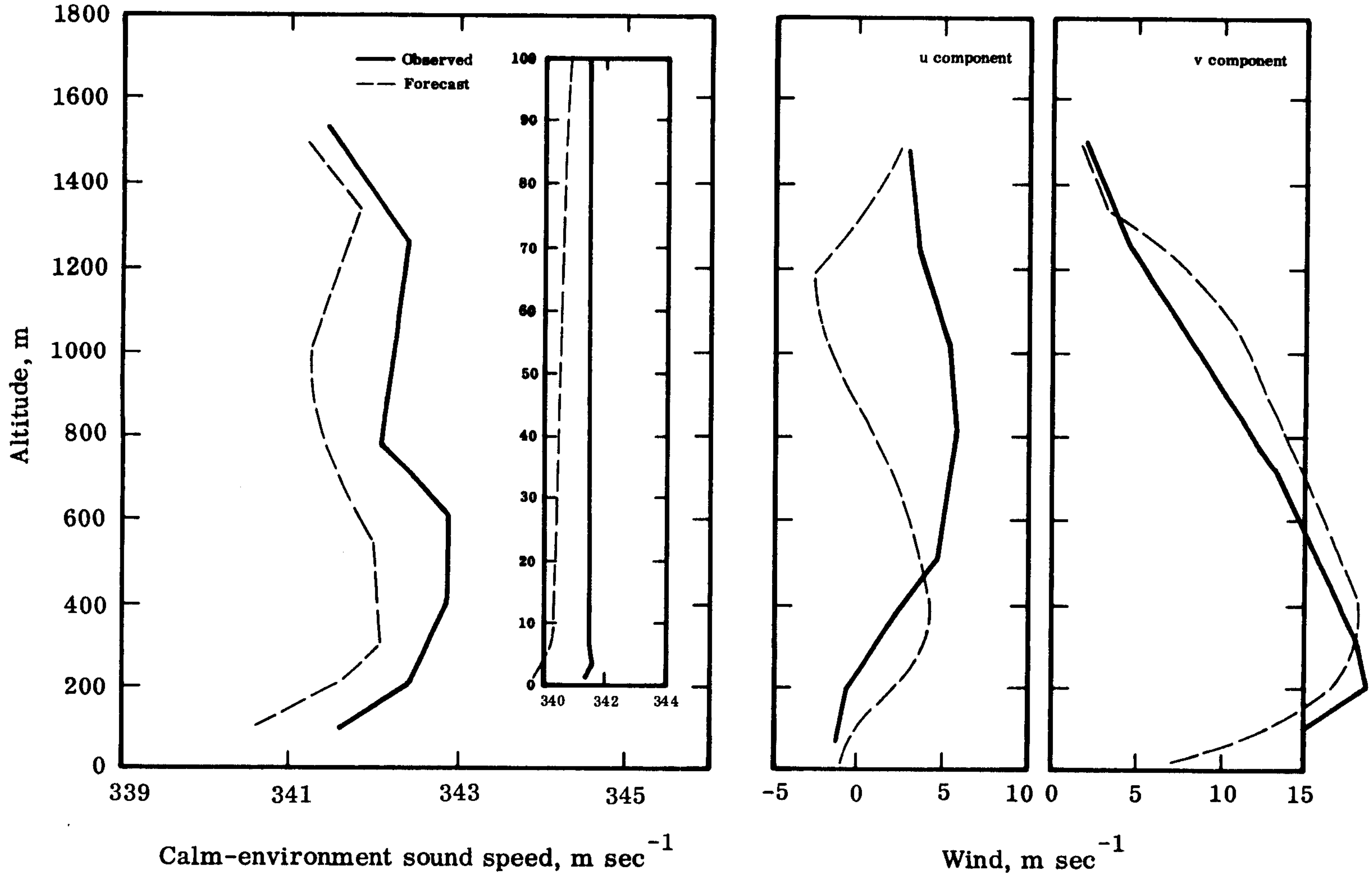

Fig. 3. Calm-environment sound speed and wind components: 8—9 August 1953. (d) Observed and 6-hr forecast: 0235 CST.

For a thorough analysis of these and other forecasts made with the model, reference should be made to the previously cited research reports.

The synoptic-scale model, developed for the U.S. Air Force [14, 15] as a method for predicting low cloudiness, holds promise as a means for obtaining longer period forecasts of sound propagation and diffusion characteristics. Experimental computations have been conducted for three synoptic cases in which 12-hr forecasts were made on a ten by ten grid located in the eastern United States (see Fig. 4).

As indicated earlier, this model requires only routine meteorological data as input. The grid shown in Fig. 4 was selected as representing the maximum resolution possible with a thorough analysis of synoptic surface and upper-air observations.

The wind field predicted by the model is based on geostrophic wind predictions and estimates of the surface stress by means of Lettau's empirical geostrophic drag coefficient formula [23]. For this reason, the accuracy potential of the horizontal wind-field predictions must be judged to be somewhat less than that of the sub-synoptic-scale model. The results seem to indicate that the temperature predictions are sufficiently accurate to permit the successful specification of the profile of the calm-environment sound-speed profile and to permit a meaningful estimate of the low-level static stability for diffusion work. The wind profiles are not so well predicted, but are reasonably accurate in some of the reported cases.

Figure 5 shows two examples of sound-speed profiles derived from 12-hr predictions. In both cases, the calm-environment profile is in rather good agreement with the observed. The profiles taking wind into account are also shown for two azimuths. Important features of the observed profiles are reproduced in the predicted profiles for the case illustrated in Fig. 5(a). A serious error in the 90° azimuth profile can be noted in Fig. 5(b). In this connection, it should be pointed out that the winds plotted in the two parts of the figure are those observed by rawinsonde. For this reason, they are subject to well-known inaccuracy and non-representativeness [17]. This does not necessarily imply that the predicted winds are more accurate than the figures indicate, but merely emphasizes the uncertainty involved in wind prediction and observation.

Before concluding this section, it is important to point out the following. Physical-numerical prediction models of whatever type require adequate initial data over an extensive horizontal domain. The prediction of the state of the atmosphere,

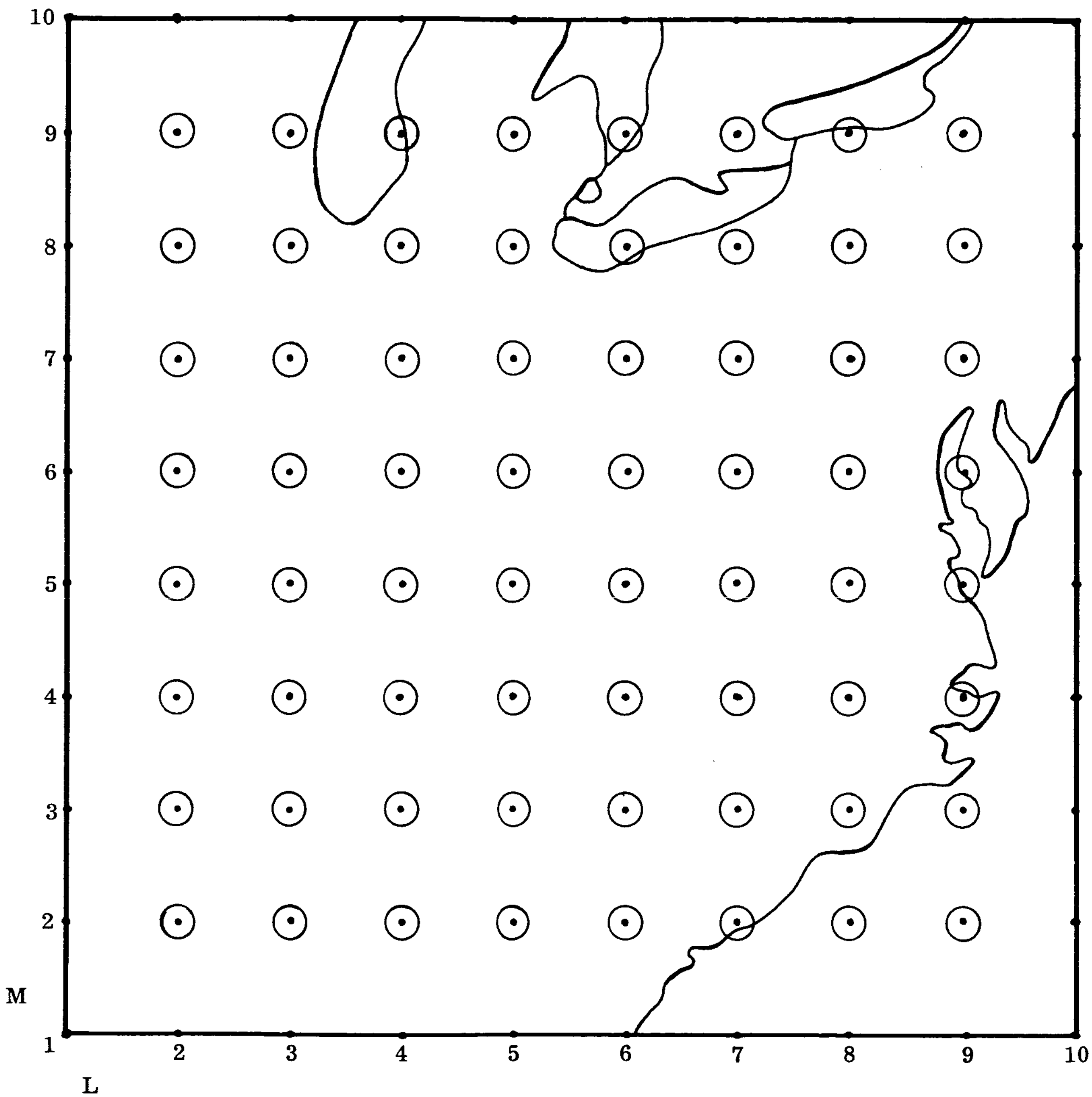

Fig. 4. Grid-point network used in experiments with synoptic-scale model.

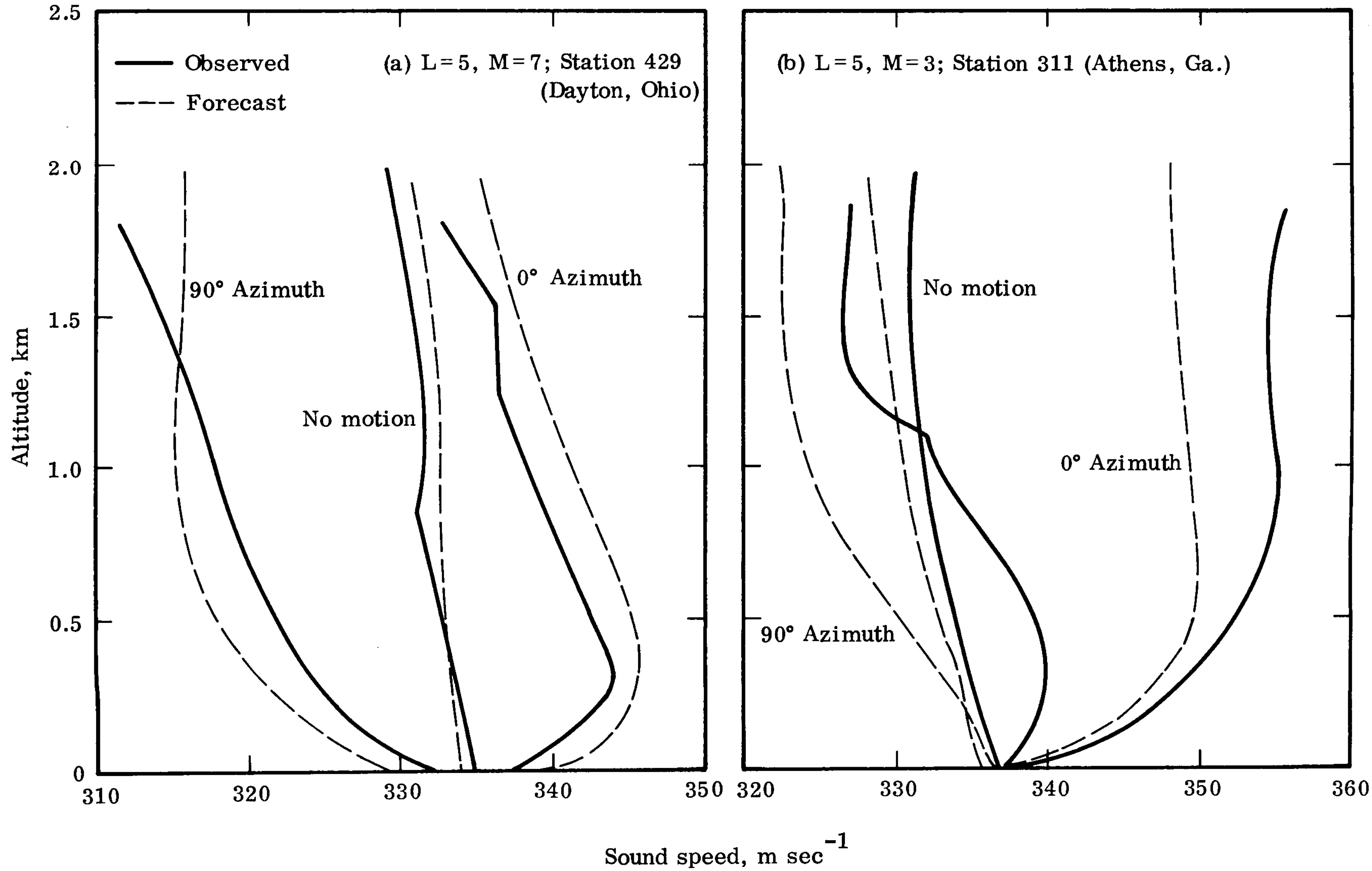

Fig. 5. Observed and 12-hr forecasts of no-motion sound speed, sound velocity to the 90° azimuth (north), and sound velocity to the 0° azimuth (east). Valid time is 00Z 7 February 1964.

at a fixed point at a time T hours into the future, requires the specification of the initial state in a region extending a distance T $\times$ U (U is the mean wind speed) meters upstream. This fact arises from the hyperbolic character of the fundamental equations governing the atmosphere. The location of test facilities on coastal waters makes the adequate specification of the initial state with routine synoptic observations impossible. Almost no upper-air data is available over these coastal waters, and extrapolation of analysis over the coastal regions is often unrealistic due to the essentially different character of the underlying surface. It is technically necessary to consider this requirement in any plan for implementing a physical-numerical prediction model.

D. Jet-stream Prediction

Many articles from the literature have documented the need for obtaining a knowledge of the vertical wind profile to determine the behavior of a vertically-rising aerospace vehicle [5, 22, 42]. This need is particularly acute in the vicinity of the layer of maximum wind where excessively-high horizontal wind speeds and vertical wind shears may be encountered [44]. An evaluation experiment was performed in which four possible techniques for the prediction of critical wind profile parameters were compared and the suitability of each assessed, considering the specialized uses to which the predictions must be applied. The four prediction techniques evaluated are:

(a) 3-level model* (simulated)
(b) GWC 6-level model† (numerical baroclinic)
(c) TRC level of maximum wind (LMW) predictions
(d) Persistence

Results of the evaluation of these four techniques were compared with a verification study of Cape Kennedy subjective operational forecasts.

An explanatory comment should be made here. It is recognized that the output of a 3- or 6-level baroclinic model is not designed to yield detailed predictions of the wind profile. An important purpose of the verification study was to determine if an

*Levels are 850, 500 and 200 mb.
†Levels are 850, 700, 500, 300, 200 and 100 mb.

improvement in profile definition is achieved by statistical modeling and, if so, what effect this improvement has on the prediction of parameters critical to NASA/MSFC operations. Persistence, as a control prediction technique, is useful in assessing the significance of any improvements.

Before describing the prediction parameters and the verification procedures, a few brief comments about the prediction techniques are required. The Air Force operational models prior to January 1965 provided estimates of height, winds, and temperature at 850, 700, 500, 300, 200 and 100 mb. The model may be described as a 2-level baroclinic (JNWP "mesh") model from 850 to 500 mb and a multi-level baroclinic model from 500 to 100 mb. Because predictions from the NMC model are not available for this period, the GWC operational forecasts at the appropriate three levels (850, 500 and 200 mb) are used to simulate a 3-level model. The TRC (LMW) physical-statistical modeling technique utilizes diagnostic regression equations in conjunction with the numerical-prediction model output to predict the level of maximum wind (LMW) variables and associated shears [39]. Endlich and McLean's jet-stream model [6, 7] is applied to the jet cores given by the wind-speed analyses in order to sharpen the jet.

A 7-day sample of data from 9 to 15 December 1964 was available for the evaluation of the various techniques. All techniques were verified with station observations, which necessitates the comparison of grid-point and station data. The ten stations and associated NWP grid points located primarily in the southeastern United States are shown in Fig. 6. The greatest horizontal distance between a station and its associated grid point is approximately 80 km. The errors involved in comparing the grid points and stations are less than those already inherent in the observational system. Radiosonde observations over a wide area in the southeastern United States were used to include a variety of wind profile types. The data used to obtain the dynamical predictions at grid points were collected under another contract.

Three distinct problems were evident in computing the LMW height, wind speed, wind direction, and vector and scalar shears above and below the LMW from the radiosonde and rawinsonde data. These problems, which result in a certain amount of noise in the verification statistics, are:

(a) Soundings with a broad layer of maximum wind (3—6 km thick) rather than with a distinct band of maximum wind speed concentrated near a particular level. As a result, in some instances, the computed wind shears are actually smaller than those encountered below and above the region of maximum winds;

(b) Wind profiles in which two or more distinct wind maxima at clearly separate levels occur (i.e., both the polar and subtropical jets are located over the station). A consequence is that for a given observation time, the LMW parameters are representative of only one maximum. Discontinuities in the LMW parameter values may result;

(c) Observation times where, due to missing data at jet-stream levels, the LMW parameters and shears can not be computed. Because missing data occurs most frequently under conditions of strong wind speeds, the overall average magnitude of speeds and shears found in the sample is somewhat reduced from the true magnitude. For example, the average maximum wind speed of 47 m sec^{-1} for all stations and all observation times is undoubtedly lower than that which would have been obtained from the sample if no data were missing.

It should be noted that, at present, TRC is working under another contract to develop an objective analysis and prediction technique for a layer of maximum wind (LRMW), suggested as a jet-stream analysis tool by Reiter [37]. This work should help to overcome the problems cited above. The technique will analyze and predict the following LRMW parameters:

(a) the mean altitude of the LRMW (bounded by levels where the wind speed is 85% of the maximum speed in the layer),

(b) the thickness of the LRMW,

(c) the maximum wind speed in the LRMW,

(d) the mean wind direction in the LRMW,

(e) the vertical vector shear and the maximum shear below the LRMW, and

(f) the vertical vector shear and the maximum shear above the LRMW.

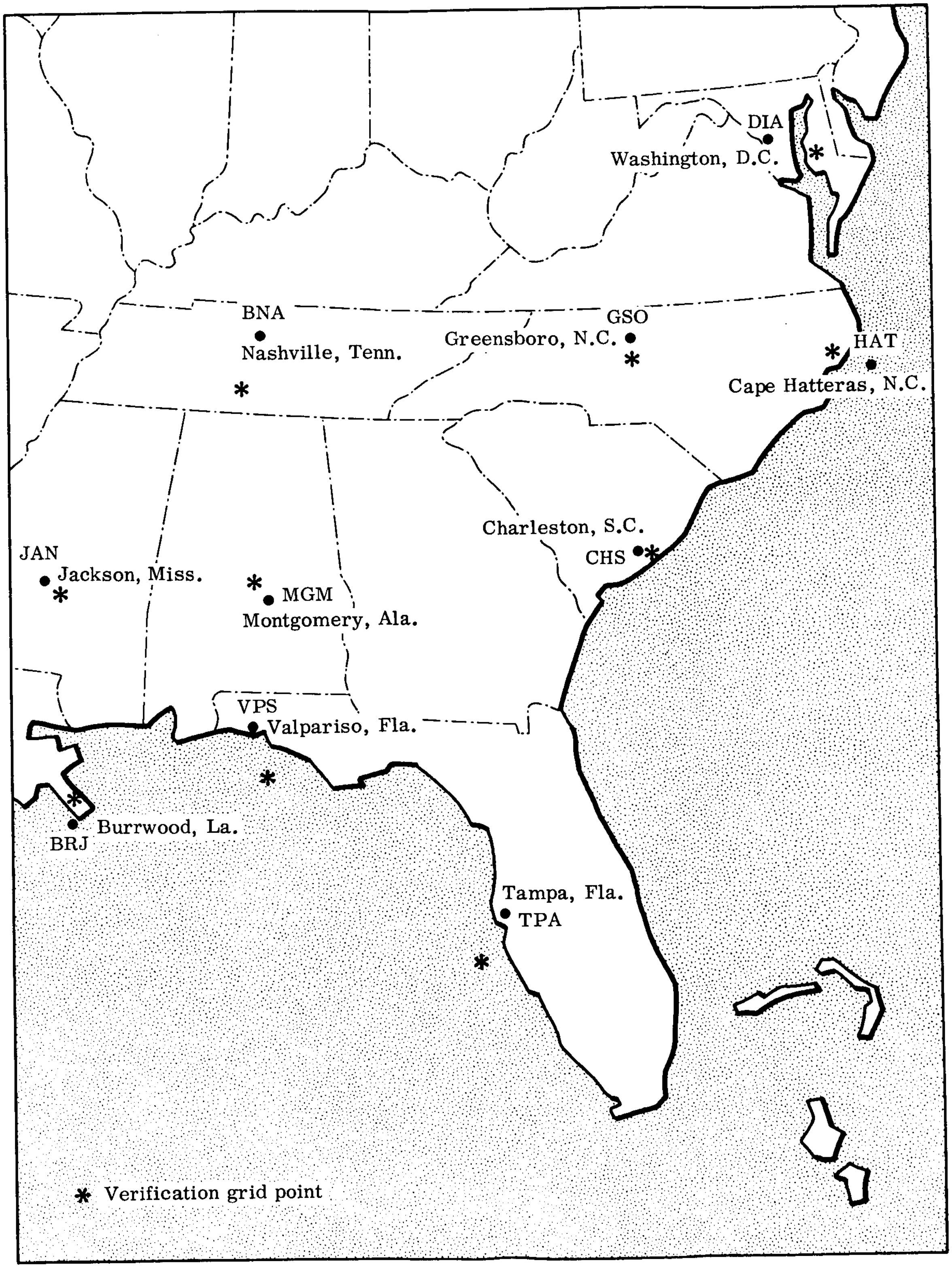

Fig. 6. Location of station grid-point pairs used in LMW verification study.

In Appendix D, Fig. D-1 illustrates typical examples of the types of profiles encountered in the data sample. It is obvious from examining the figures that the selection of a LMW and the computation of meaningful shears above and below this level is a difficult task. The presence of these types of profiles accounts, to a large degree, for the high rms errors that were obtained with all techniques in predicting the height of the LMW and the shears above and below the LMW. Both scalar and vector shears were computed above and below the LMW in 300- and 1500-m layers. Because results were similar for both scalar and vector shears, the scalar shear verifications are omitted. The wind speed and direction at the LMW were combined to determine a vector error.

In computing the predicted shears, the following levels were used for the different techniques:

(a) 3-level: 500 and 200 mb

(b) 6-level: 500, 300, 200, and 100 mb

(c) LMW modeling: 500, 300, 200, and 100 mb, and LMW (predicted).

In nearly every case for the 3-level predictions, the level of maximum wind is at 200 mb, and no shears above are computed for this prediction technique. The shears above, in most cases, are computed using 200- and 100-mb data for the 6-level predictions, and LMW and 100-mb data for the LMW predictions. Thus, most predicted shears above the LMW are gross, linear approximations due to the limitations of the prediction techniques.

The shears below the LMW for the 6-level and LMW modeling prediction techniques are usually computed for layers of less vertical extent. Most 6-level shears below are computed using 200- and 300-mb data, while the LMW modeling shears are computed, in most cases, using LMW and 200- or 300-mb data. Linear interpolation is employed where necessary.

The parameters that were verified for all time intervals are listed in Table 3. The skill in forecasting these parameters indicates how well a given technique forecasts the level and intensity of the maximum wind speeds, normally located near the tropopause. The ability to forecast the intense vertical wind shears associated with the LMW is also evaluated. The parameters listed in Table 3 were chosen both because of their operational significance and because the evaluation of their predictability provides clues to future avenues for improvement of forecast accuracy.

TABLE 3
WIND PROFILE PARAMETERS VERIFIED

Symbol	Description
$W_s(L)$	wind speed at level of maximum wind
$\vec{W}_s(L)$	vector wind speed at level of maximum wind
$Z(L)$	height of level of maximum wind
$S_b(3)$	vector vertical wind shear in 300-m layer below LMW
$S_b(15)$	vector vertical wind shear in 1500-m layer below LMW
$S_a(3)$	vector vertical wind shear in 300-m layer above LMW
$S_b(15)$	vector vertical wind shear in 1500-m layer above LMW

A number of questions were considered in the evaluation of the wind profile predictions. Examples of the questions are:

(a) What are the largest forecast errors? Are these errors critical, that is, could they result in a wrong go—no-go decision?

(b) Is there any bias toward over- or under-forecasting the maximum wind speed and shears and their locations?

(c) Does the use of vector rather than scalar error statistics significantly affect the evaluation?

(d) Does the LMW modeling prediction technique significantly improve the forecast of maximum wind speed, its location in the vertical and the shears above and below this location? How does this improvement compare to that which was obtained by using the 6-level model instead of the 3-level model? How do all three techniques compare with persistence?

(e) If the observed profiles are stratified into strong jets and moderate or weak jets (45 m sec^{-1} is a reasonable critical maximum wind speed), how does this affect the technique comparison?

The upper-level synoptic situation was as follows. The location and intensity of the jet-stream systems in the central and eastern United States changed considerably during the data period. A strong east-west system shifted into the Atlantic Ocean early during the period, with the result that generally light or moderate winds were prevalent during the middle of the sample period. A strong southwest-northeast flowing jet stream moved into the region by the end of sample time, causing a sharp increase in wind speeds.

Root-mean-square error statistics were obtained with each forecast technique for the four forecast intervals in two separate tests. In the first evaluation, all station observations, except when missing, were used. In the second test, only soundings containing observed maximum wind speeds of at least 45 m sec^{-1} were used. The overall rms errors for both tests are given in Tables 4 and 5. The rms errors obtained for the persistence, 3-level, 6-level and LMW modeling techniques for 12-, 24-, 36- and 48-hr forecasts are given. Because the magnitude of the rms error should be considered in the light of the observed mean and standard deviation of the variable being predicted, these have been given in Table 6 for the height, wind direction, and speed at the LMW, and the shears above and below the LMW.

A number of results are apparent from an examination of Tables 4 through 6.

(a) Perhaps the most important variables to predict with regard to NASA/MSFC operations are the LMW height, wind direction, and wind speed. The scalar and vector rms errors (in m sec^{-1}) of the forecast maximum wind are given in the third and fifth columns of Tables 4 and 5. The rms error of the LMW height (in 10^2 m) is given in the second column.

The rms errors of the height may, at first glance, seem rather high. However, one must again consider the great difficulty in determining the LMW height for many profiles (see examples in Appendix D). This difficulty contributes greatly to the magnitude of the rms error. For all but one forecast period (see Table 4), the LMW technique yields lower rms errors for both LMW height and wind velocity than the other three

TABLE 4
OVERALL rms ERRORS—ALL CASES

Prediction technique	Forecast period (hr)	$\vec{W}_s(L)$ (m sec^{-1})	Z(L) (10^2 m)	$W_s(L)$ (m sec^{-1})	$S_a(3)$ (m sec^{-1})	$S_a(15)$ (m sec^{-1})	$S_b(3)$ (m sec^{-1})	$S_b(15)$ (m sec^{-1})	No. of cases
Persistence	12	13.5	17.7	8.3	3.0	8.2	2.6	6.4	75
6-level		14.4	16.5	13.0	3.5	11.3	3.1	8.3	
3-level		15.6	15.8	14.1	—	—	3.2	8.6	
LMW		12.4	13.0	10.2	3.2	9.6	2.8	6.9	
Persistence	24	19.0	19.3	12.2	3.4	10.1	2.9	6.5	74
6-level		15.8	18.5	14.2	3.6	10.6	2.7	7.7	
3-level		16.5	16.0	15.2	—	—	2.7	7.8	
LMW		14.0	13.8	11.8	3.1	8.5	2.4	6.7	
Persistence	36	22.0	21.7	14.9	2.9	9.6	2.9	6.7	73
6-level		15.8	19.3	13.3	3.2	9.3	2.5	7.2	
3-level		16.1	18.8	14.1	—	—	2.6	7.4	
LMW		14.0	15.8	10.8	2.9	7.3	2.4	6.4	
Persistence	48	22.7	25.1	14.8	3.4	9.2	2.9	7.4	72
6-level		16.5	21.7	14.0	3.4	9.5	2.4	7.0	
3-level		17.7	21.4	15.4	—	—	2.7	7.4	
LMW		14.4	18.2	10.9	3.0	8.0	2.3	6.7	

TABLE 5
OVERALL rms ERRORS—$\vec{W}_s(L) \geq 45$ m sec^{-1}

Prediction technique	Forecast period (hr)	$\vec{W}_s(L)$ (m sec^{-1})	Z(L) (10^2 m)	$W_s(L)$ (m sec^{-1})	$S_a(3)$ (m sec^{-1})	$S_a(15)$ (m sec^{-1})	$S_b(3)$ (m sec^{-1})	$S_b(15)$ (m sec^{-1})	No. of cases
Persistence	12	14.8	16.8	10.8	3.6	10.4	3.2	8.4	31
6-level		20.1	11.9	19.0	4.4	15.2	4.1	10.6	
3-level		21.7	13.5	20.5	—	—	4.1	11.1	
LMW		16.6	10.0	14.9	4.2	13.7	3.7	9.0	
Persistence	24	23.6	19.5	15.8	4.1	13.8	3.7	8.2	30
6-level		22.4	16.7	21.2	4.5	14.0	3.3	10.5	
3-level		23.5	14.2	22.5	—	—	3.3	10.4	
LMW		19.4	11.0	17.4	4.1	11.7	3.2	9.3	
Persistence	36	25.5	18.4	16.3	3.1	11.2	3.6	7.8	30
6-level		21.2	15.0	19.3	4.1	12.0	3.2	9.9	
3-level		22.0	18.3	20.5	—	—	3.3	10.2	
LMW		17.6	14.2	14.8	3.6	9.4	3.0	9.0	
Persistence	48	25.5	23.4	15.4	3.5	9.6	3.4	8.8	32
6-level		21.4	17.8	19.2	4.1	12.0	2.9	9.4	
3-level		23.3	20.2	21.2	—	—	3.2	10.0	
LMW		17.2	17.6	13.9	3.8	10.5	3.0	9.0	

TABLE 6
MEANS AND STANDARD DEVIATIONS OF VARIABLES
COMPUTED FROM OBSERVATIONS (100 cases)

Variable	Unit	Mean	Standard deviation
$Z(L)$	km	11.2	1.6
$W_s(L)$	m sec^{-1}	47.4	13.8
$S_a(3)$	m sec^{-1} $(0.3 \text{ km})^{-1}$	3.2	2.5
$S_a(15)$	m sec^{-1} $(1.5 \text{ km})^{-1}$	11.6	7.1
$S_b(3)$	m sec^{-1} $(0.3 \text{ km})^{-1}$	3.0	2.1
$S_b(15)$	m sec^{-1} $(1.5 \text{ km})^{-1}$	9.9	5.7

techniques. The 12-hr persistence forecast of maximum wind yields a lower scalar (but not vector) rms error. Note that the difference between vector and scalar rms errors for wind forecasts is much greater for persistence than any of the other three forecasting techniques. This indicates that definite skill is present in the predicted changes in wind direction made by the Offutt numerical model. (The LMW modeling technique wind direction forecast is tied directly to the Offutt model.) As would be expected, the rms errors for each of the forecasting techniques generally increases with progressively longer forecast intervals. The increase in height rms errors is fairly uniform from 12- to 48-hr forecasts, while the vector and scalar wind rms errors show the greatest increase between 12- and 24-hr predictions.

(b) An examination of Table 5 indicates that, regardless of the prediction technique used or forecast interval, larger rms errors occur in the sample limited to the strong wind speeds than in the entire sample, with the exception of the LMW height. It should be remembered, however, that percentage error is undoubtedly smaller. The rms error of the height predictions is considerably lower, indicating the more regular movement of the LMW under strong jet-stream conditions.

The modeling technique yields the lowest rms errors for predictions of LMW height (all forecast intervals) and 24-, 36-, and 48-hr forecasts of LMW wind velocity (vector error). Persistence forecasts yield lower scalar rms errors for 12- and 24-hr predictions of LMW wind speed. For all techniques, the vector and scalar wind rms errors increase markedly between 12- and 24-hr forecasts, with generally lower values for 36- and 48-hr forecasts. The rms error for height, however, is greatest for 48-hr forecasts.

Perhaps the single most important set of error statistics in the two tables is the vector wind rms error under strong wind conditions (third column of Table 5). Persistence is slightly superior to the LMW modeling technique for 12-hr forecasts. However, for 24-, 36-, and 48-hr forecast intervals, vector rms errors change little, and representative values for each technique are: Persistence, 25 m sec^{-1}; 3-level, 23 m sec^{-1}; 6-level, 21 m sec^{-1}; and LMW, 18 m sec^{-1}.

Thus, when a strong jet stream is present, the following is noted:

(1) Under conditions of a strong wind speed (and shears), the LMW modeling technique was demonstrated to yield significantly lower vector wind rms errors for longer-term forecasts (24-, 36-, and 48-hr intervals) than either persistence or the 3-level or 6-level technique.

(2) Persistence yields the best 12-hr forecast of LMW wind speed. This is not true when all cases are considered, and indicates, of course, the smaller percentage variability of the wind under strong jet-stream conditions.

(c) The rms errors for the vertical wind shear above and below the LMW are high, regardless of the prediction technique used. It must be remembered that the determination of vertical wind shears above and below the LMW is complicated by profiles exhibiting several distinct maxima or a broad layer of maximum winds.

Considering all cases, the LMW modeling prediction technique produces lower rms errors for 24-, 36-, and 48-hr forecasts of vertical wind shear than forecasts obtained from the 3-level and 6-level models or persistence. Although a great deal of "noise" is undoubtedly present in the rms error statistics for reasons stated earlier, there is no reason to doubt the relative merit of the techniques as reflected in the statistics.

Tables 4 and 5 show that, in general, the rms errors do not increase for the 36- and 48-hr forecasts. The reason for this surprising result is understood when one considers the valid times for each of the four forecast intervals. They are (a) 12-hr, 12Z 9 December to 12Z 13 December; (b) 24-hr, 00Z 10 December to 00Z 14 December; (c) 36-hr, 12Z 10 December to 12Z 14 December; and (d) 48-hr, 00Z 11 December to 00Z 15 December. This approach was used to fully utilize the limited sample and at the same time to retain a comparable number of cases in each forecast interval. Figure 7(a) shows that the 24-hr forecasts of maximum wind velocity for all techniques resulted in large rms errors at 00Z 10 December and 12Z 10 December, due to rapid changes in maximum wind speed at many stations. 48-hr forecasts were not made for these two valid times [see Fig. 7(b)], and only an approximate comparison of rms errors for different forecast intervals can be made. A comparison of the two parts of Fig. 7 shows that, for those valid times where both 24- and 48-hr forecasts were made, the rms errors of the 48-hr forecasts were usually higher. The comparison of different techniques within the <u>same</u> forecast interval is exact (paired comparison).

A recent wind forecast verification study made at Cape Kennedy [18] provides additional useful information. Subjective forecasts (20 to 30 hours prior to verification time) of wind direction and wind speed in 5000 ft intervals from 5000 ft to 100,000 ft are compared with a forecast of persistence (no change) at Cape Kennedy. Data for two years (117 wind profile forecasts made in 1963 and 1964) are divided into four seasons. Both the velocity (vector) and speed errors are computed at each level for the subjective and persistence forecasts. Table 7 summarizes some of the error statistics found in [18]. The largest rms errors, both vector and scalar, together with the level at which they are found, are given for both forecasts. Although the magnitude of the rms errors is greatest at jet-stream levels, the percent error

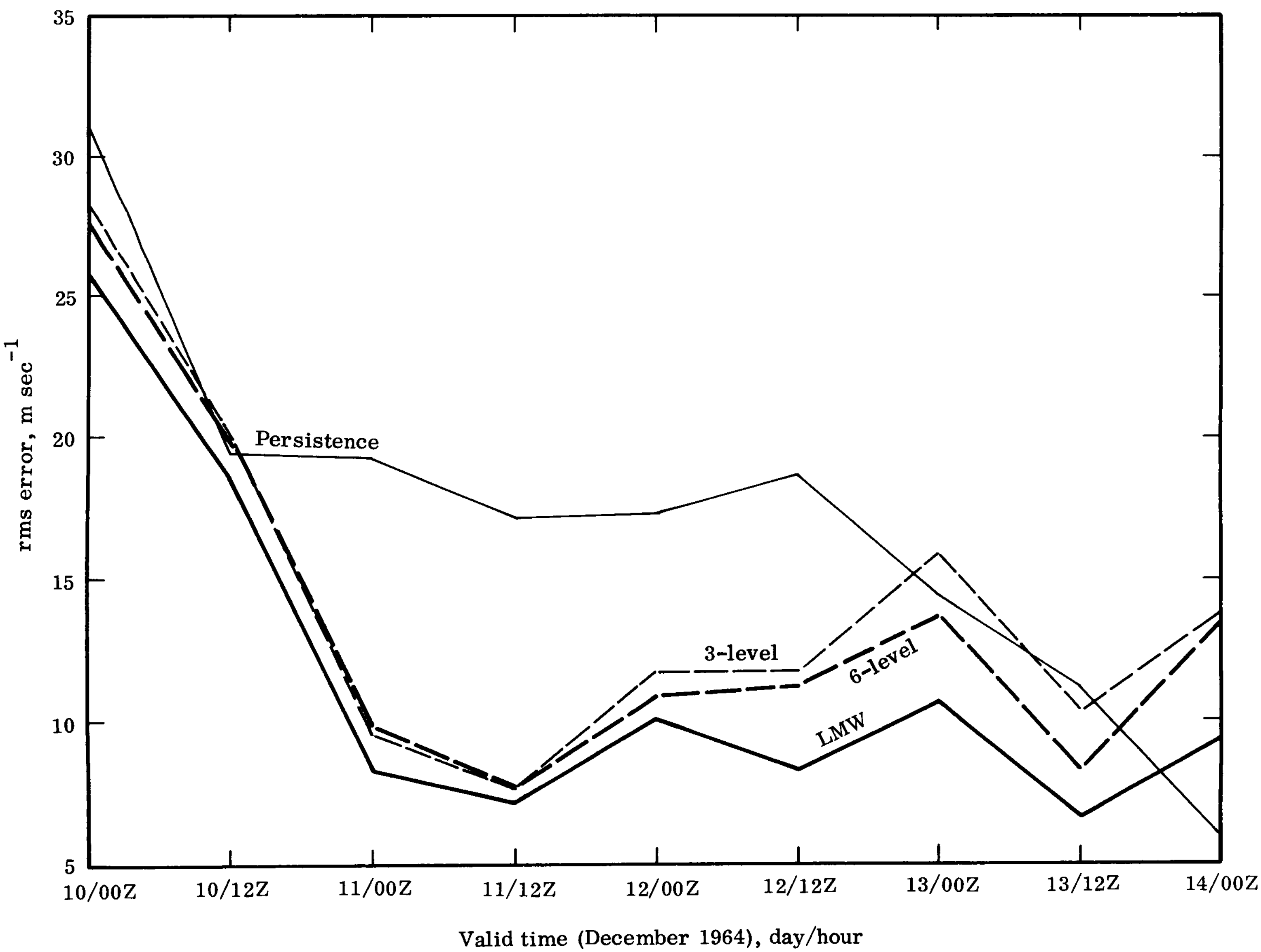

Fig. 7. Vector rms error of $\vec{W}_s(L)$. (a) 24-hr forecast (74 cases).

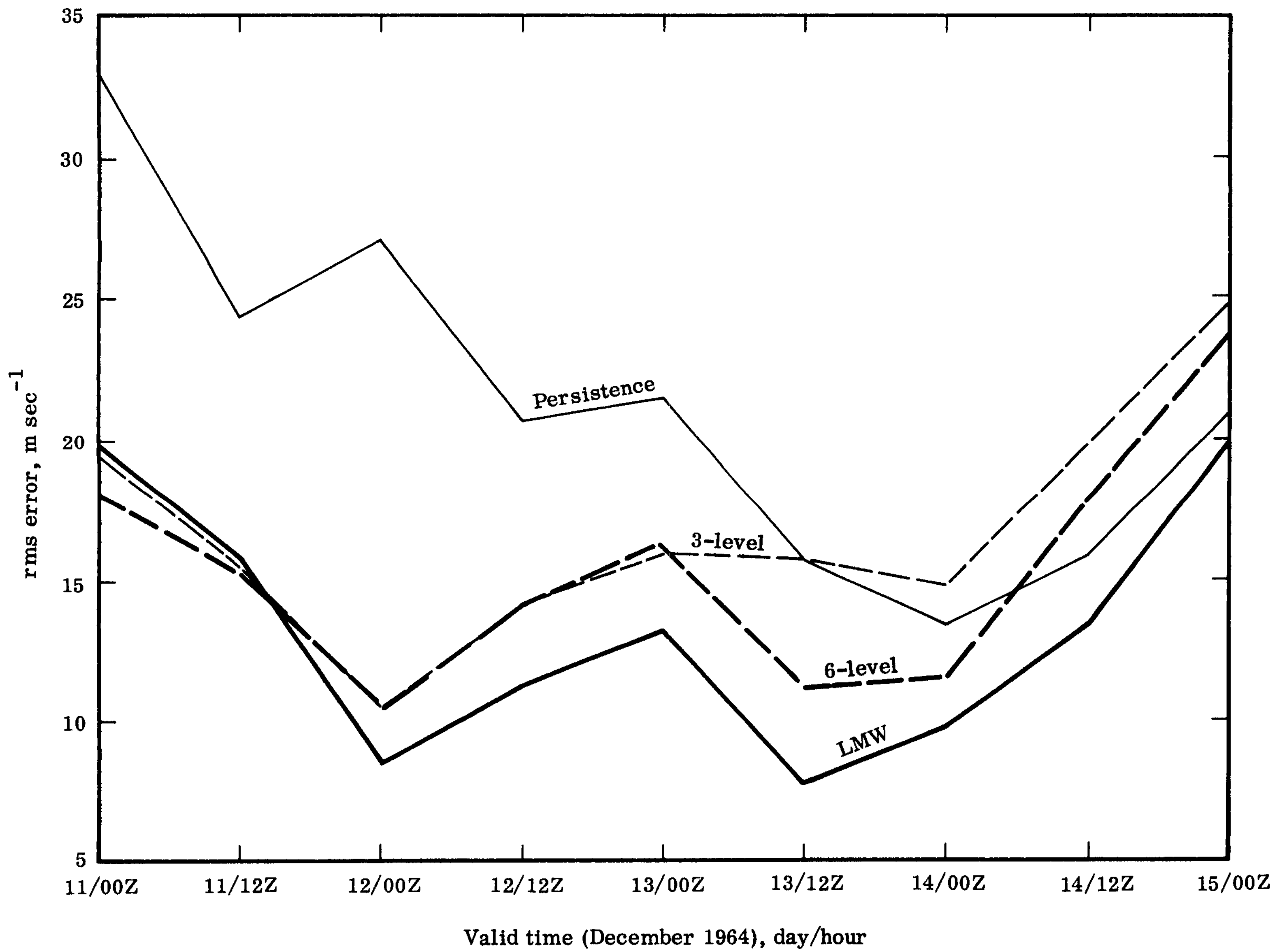

Fig. 7. Vector rms error of $\vec{W}_s(L)$. (b) 48-hr forecast (72 cases).

is lower. The speed forecast error contributes roughly 65% to the vector error. No bias with regard to over- or under-forecasting occurs. Considering all levels, it was noted that in general, the subjective forecast is superior to persistence by roughly 6—8% of the observed wind speed [18].

The greatest vector errors occur in the spring when the jet stream is still relatively strong and is also subject to rapid changes. During the summer, when errors are relatively small, the subjective forecasts are not superior to persistence at jet-stream levels.

TABLE 7
GREATEST VECTOR AND SPEED rms ERRORS FOR SUBJECTIVE AND PERSISTENCE FORECASTS (from [18])

(117 cases for all seasons)

Season	Forecast type	Level of greatest vector error (km)	rms error Vector ($m\ sec^{-1}$)	rms error Speed ($m\ sec^{-1}$)	Level of greatest speed error (km)
Winter	Persistence	10.7	15.9	11.1	10.7
	Subjective	12.2	13.2	8.9	10.7
Spring	Persistence	12.2	17.1	9.9	12.2
	Subjective	12.2	14.6	9.3	12.2
Summer	Persistence	10.7	9.8	6.8	10.7
	Subjective	10.7	10.7	7.7	12.2
Fall	Persistence	10.7	14.6	11.0	9.1
	Subjective	12.2	13.4	9.5	10.7

It is instructive to compare the persistence vector and scalar wind rms errors obtained at Cape Kennedy with the 24-hr persistence rms errors obtained in the verification study described here. The rms error statistics discussed here are for 10 stations, within a 7-day data period. The Cape Kennedy statistics are for a single station, with cases occurring over a period of several months. The error statistics given in the study described here are most comparable to the "winter" subsection of the Cape Kennedy data. The errors at Cape Kennedy at jet-stream levels are compared with the LMW modeling technique errors in Table 8. The 24-hr persistence vector wind rms errors indicate that the maximum wind velocity at the 10 stations used in the verification study was probably stronger and more variable during the data period than the average maximum wind speed conditions in the Cape Kennedy winter sample. At Cape Kennedy, the vector wind rms error is lowered 23.7% at 10.7 km using subjective forecasting procedures. The percentage reduction is much less at 12.2 km and no reduction is obtained at 13.7 km. Using the objective LMW modeling prediction technique, the 24-hr vector wind rms error is reduced 26.3%. The average height of the LMW was 11.3 km. Johannessen [21] has indicated that in middle latitudes an average improvement of 30 to 35% over the persistence vector wind rms error is possible near or just below jet-stream levels.

TABLE 8
COMPARISON OF PERSISTENCE, SUBJECTIVE, AND OBJECTIVE
24-hr* FORECASTS OF WIND VELOCITY

Level (km)	Vector rms error (m sec^{-1})			Percent improvements
	Persistence	Subjective	Objective	$\left(\frac{\text{Persistence minus forecast}}{\text{persistence}} \times 100\right)$
10.7	15.9	12.1	—	23.7
12.2	14.2	13.2	—	7.0
13.7	12.1	12.2	—	-0.8
LMW	19.0	—	14.0	26.3

*The rms errors given for the 10.7-, 12.2- and 13.7-km levels are for a variable forecast interval of 20—30 hours.

This limited indirect comparison implies that objective procedures for predicting maximum wind velocity are, at the very least, competitive with subjective forecasts for a 24-hr forecast interval.

A large number of scatter diagrams (plotting forecast versus observed values) and graphs showing individual rms errors for each observation time (e.g., see Fig. 7) were constructed for different forecast techniques and lags. The purpose of these graphs was to determine (a) the error variability and associated meteorological events, (b) extreme errors, and (c) existence of bias in the prediction methods.

Figure 8 depicts scatter diagrams of observed versus LMW modeling 24-hr forecasts of LMW speed and height. Each plotted dot is a forecast with the corresponding observation (74 cases).

Figure 8(a) clearly shows that, in general, there is good agreement between forecast and observed values. There is a tendency to under-forecast the magnitude of the LMW wind speed, because more points are above than below the line of perfect agreement between forecast and observation. The problem of under-prediction and the magnitude of the extreme errors is greater in the 3- and 6-level predictions than in the LMW modeling predictions. Because most observed LMW wind speeds of operational interest (at least 50 m sec^{-1}) are under-forecast, the possibility exists of making an incorrect decision for the initiation of a scheduled vehicle launch.

Figure 8(b) shows that there is a tendency to over-predict the height of the LMW for the period considered. Considering the problems involved in defining the LMW, most forecasts are reasonably good—the predicted height usually being within 1.5 km or less of the observed height.

The problem of under- or over-prediction can be summed up with the following set of numbers: The mean observed LMW wind speed for all cases is 47 m sec^{-1}; the mean 24-hr LMW modeling predictions are 39 m sec^{-1}; the mean 24-hr 6-level predictions are 34 m sec^{-1}; the mean observed height of the LMW is 11.2 km, and; the mean 24-hr LMW modeling prediction is 11.8 km.

E. Physical-statistical-synoptic Profile Prediction

The National Meteorological Center (NMC) transmits a large number of prognostic charts for various levels in the atmosphere for time periods up to 72 hours. Table 9 lists the charts, number, transmission and verifying time. It would be desirable to use this multitude of prognostic information to attempt to derive wind and temperature profile predictions.

We designed a technique whereby profile forecasts are generated from the surface to 10 mb (~30 km) for periods to 36 hours. (Predictions can be extended to 48 and 72 hours if the results up to 36 hours appear to warrant the extension.) The technique makes use of:

(a) the NMC prognoses,

(b) hydrostatic and pressure-gradient relationships,

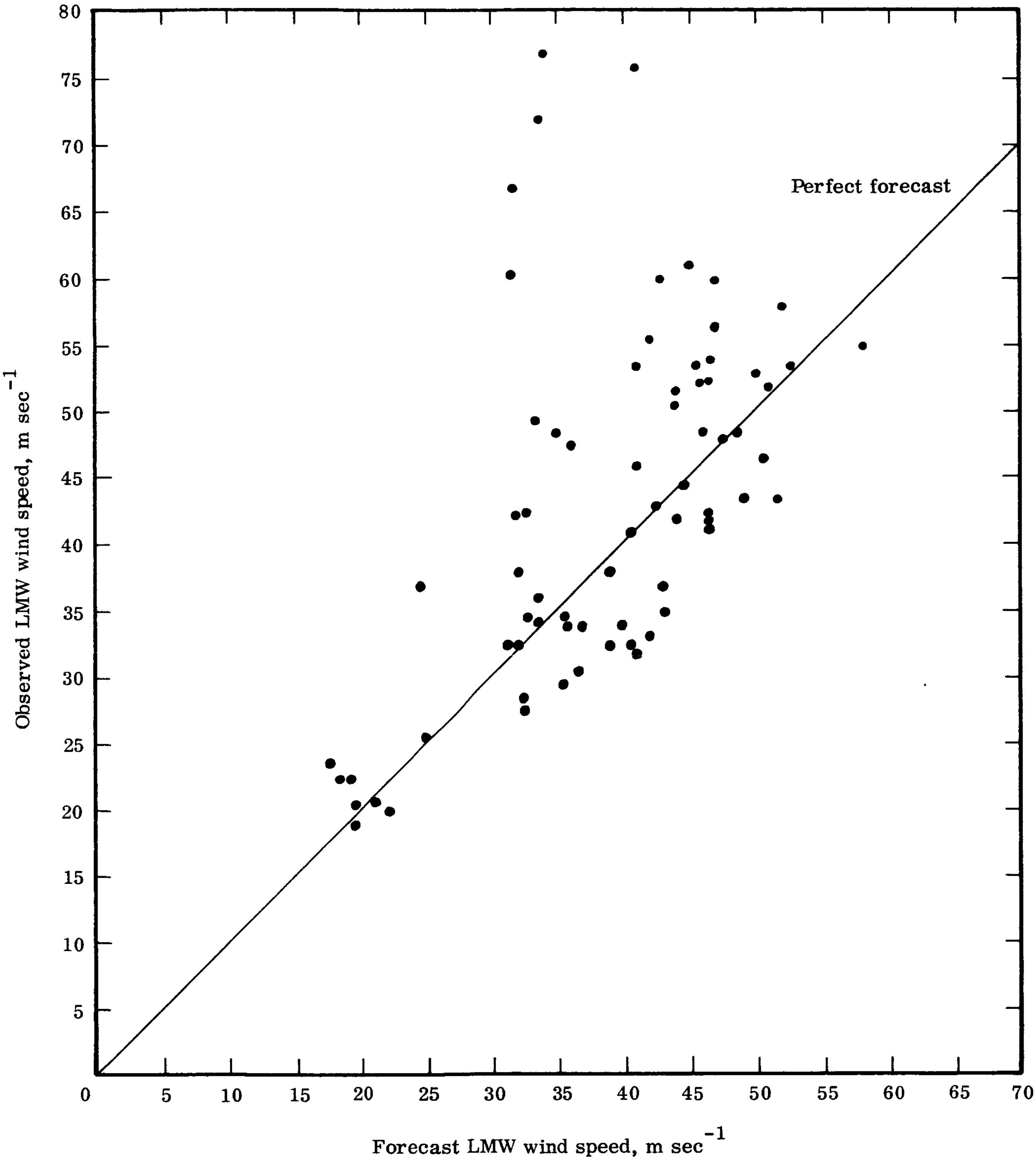

Fig. 8. Observed versus LMW-modeling 24-hr forecasts (74 cases). (a) LMW wind speed.

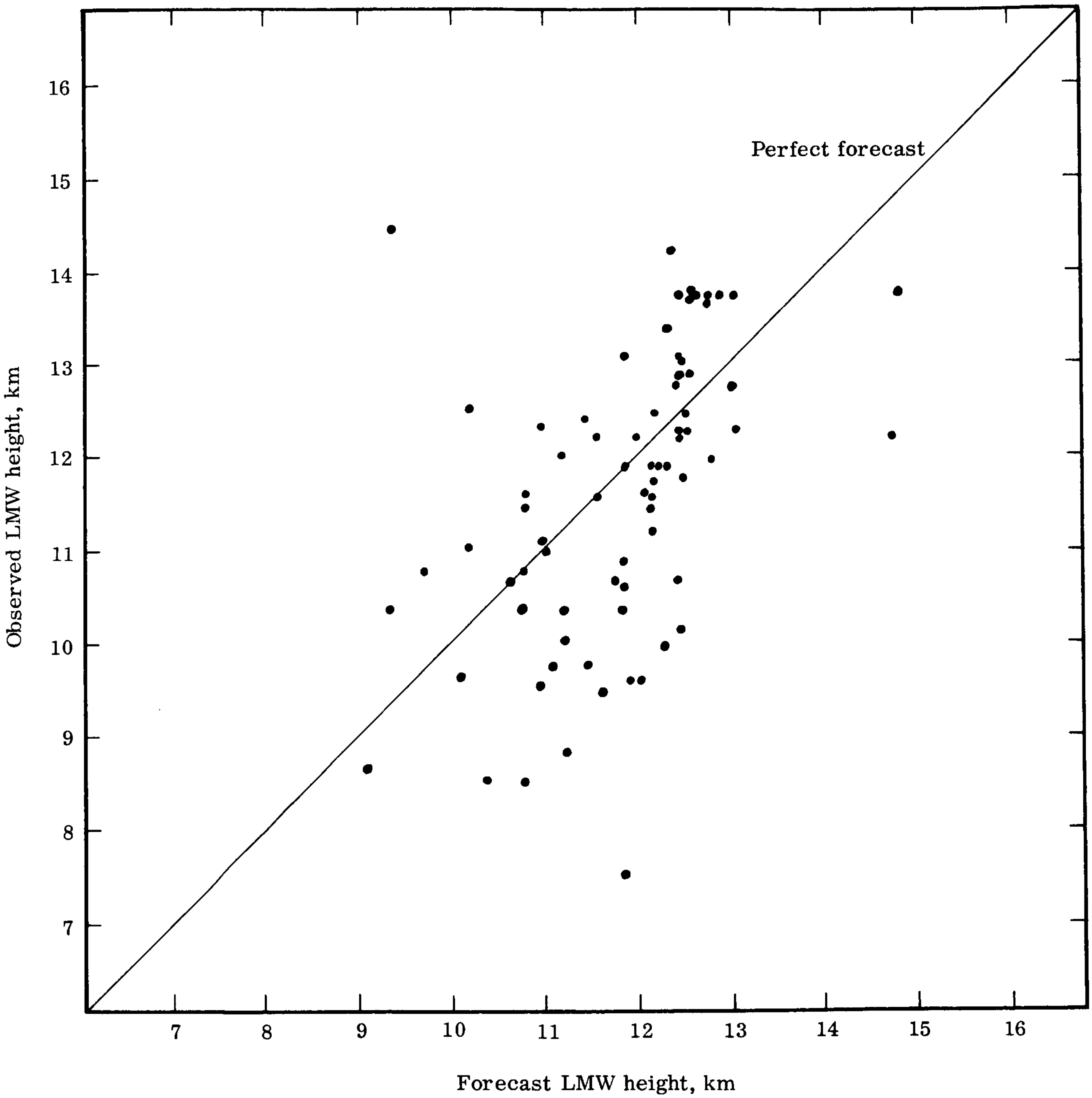

Fig. 8. Observed versus LMW-modeling 24-hr forecasts (74 cases). (b) LMW heights.

TABLE 9
NMC PROGNOSES

Chart	No.	GMT transmission time	GMT verifying time	No.	GMT transmission time	GMT verifying time
5-day or 72-hr forecast (Mon, Wed, Fri, and Sun, Tues, Thurs, Sat, respectively)	1	0000				
72-hr, 500-mb forecast	4	0102	1200	66	1302	0000
Vorticity and 500-mb initial conditions, and 12-, 24-, and 36-hr barotropic forecast	11	0247	1200 0000 1200	73	1447	0000 1200 0000
12- and 24-hr forecast of surface pressure, clouds, and precipitation	12	0302	1200 0000	74	1502	0000 1200
High-level significant weather forecast	19	0414	1800	82	1624	0600
36-hr, 500-mb baroclinic forecast	36	0702	1200	94	1906	0000
24- and 48-hr, 500-mb baroclinic forecast	37	0712	0000	95	1916	1200
Vorticity and 500-mb initial conditions, and 12-, 24-, and 36-hr baroclinic forecast	38	0722	1200 0000 1200	96	1926	0000 1200 0000
24- and 48-hr forecast of surface pressure, clouds, and precipitation	42	0840	0000	100	2044	1200
24-hr, 300- and 200-mb forecast	46	0920	0000	104	2120	1200
24-hr, 850- and 700-mb forecast	47	0930	0000	105	2130	1200
36-hr, 700-mb forecast	51	1012	1200	109	2212	0000
36-hr, 300-mb forecast	52	1022	1200	110	2222	0000
30-hr forecast of surface pressure and precipitation, and 36-hr forecast of 1000—500-mb thickness	54	1052	1200	113	2258	0000
24-, 48-, and 72-hr minimum temperature forecasts	62	1210	1200			
24-, 48-, and 72-hr maximum temperature forecasts	117	2344	0000			

(c) a trajectory method, and

(d) the equations developed at TRC for vertical extrapolation of heights and temperature for all mandatory constant-pressure surfaces from 300 to 10 mb [34, 40, 41].

This is the type of technique that can be used at a weather station; the details of it are contained in Appendix E.

A 20-day collection of NMC prognoses and analyses of constant-pressure surfaces, and radiosonde data for October 1965, were used to test the technique. Nashville, Tennessee, the nearest RAOB station to Huntsville, was chosen as the station for which verifications would be performed. Of this collection, only seven observation times had a complete set of charts and observed data necessary for verification. The reduced sample that could be used from the complete 20-day period resulted from missing 50-, 30- and 10-mb data and/or because some prognostic charts were not received for various reasons. The charts required to generate the 12-, 24-, and 36-hr profile forecasts are shown in Table 10.

All of the prognostic information and most of the analyses except the 250-, 150-, 50-, 30-, and 10-mb analyses are NMC products transmitted via the national facsimile network. For the analyses not transmitted, radiosonde data was used for analysis in the area of interest.

Although the technique provides forecasts at all mandatory levels from the surface to 30 km, its primary purpose is to generate predictions for stratospheric levels from 100 to 10 mb (~ 16 to 30 km). The techniques given in Section II, A—D, are for low- and mid-tropospheric levels. The verifications discussed in those sections are considered representative of the present state of the art for tropospheric profile prediction. Although tropospheric levels (850, 700, 500, 300 and 200 mb) were verified in the course of the evaluation of this technique, there was little additional information that could be obtained from the error statistics; there are two reasons for this: (a) numerical prognoses are common input to almost all prediction techniques investigated, and (b) the sample size was small (7 cases) relative to the sample size in the verifications of the other techniques. Thus, in the following, results for the tropospheric levels are discussed only in general terms, while more detailed results are presented for stratospheric levels.

TABLE 10
ANALYSIS AND PROGNOSTIC CHARTS USED IN VERTICAL EXTRAPOLATION PREDICTION TECHNIQUE

Initial-time analysis charts (mb)	Prognostic charts		
	12-hr (mb)	24-hr (mb)	36-hr (mb)
Surface pressure	500	Surface pressure	Surface pressure
850		850	700
700		700	500
500		500	300
300		300	
250		200	1000—500 thickness
200			
150			
100			
50			
30			
10			

It is necessary to keep in mind the small sample size when evaluating the error statistics presented in this section. They are meant only to indicate, in a general sense, whether the technique is worthwhile to use as an aid in generating profile forecasts for the stratosphere. Firm conclusions cannot be drawn because of this small sample.

Two experiments were conducted to test the prediction technique.

(a) Experiment 1—All NMC constant-pressure-level prognostic charts available for 12-, 24-, and 36-hr forecast periods were used, and the NMC height analyses (used as "past" data in the regression equations) were corrected to better fit the observed wind field by using the geostrophic wind scale.

(b) Experiment 2—Only the 500-mb prognoses were used in conjunction with the vertical extrapolation height and temperature. Regression equations were used to obtain prognoses at 300, 250, and 200 mb. (NMC analyses were corrected to better fit the observed wind data as in Experiment 1.)

A total of 21 forecasts for each experiment were generated from the sample of 7 observation times (three forecasts per initial observation time).

A set of temperature and wind forecasts and observed profiles were prepared to illustrate the results for Experiments 1 and 2. Tables 11 and 12 summarize the forecast errors for temperature and wind (100 to 10 mb) for seven observation times.

The temperature profiles showed little or no difference for the two forecast methods, especially at the stratospheric levels (at levels below 300 mb the two methods are identical, (see Fig. 9). Neither method showed the small-scale features of the observed soundings, but each followed the observed profile in general characteristics.

Examination of Table 11 reveals that the difference in the average temperature forecast errors between the two experiments is insignificant. Average errors are generally between 2 and 3°C for all levels and forecast intervals. Persistence as a forecast produces errors within the same range. The difference between the two forecast methods and persistence as a forecast can also be considered insignificant. There is a tendency for persistence errors that are consistently higher than forecast errors for the 36-hr forecasts of this data sample. A larger sample is necessary to establish any firm conclusions regarding the relative merits of the forecast technique and persistence beyond the 24-hr forecast period.

Forecast wind-speed profiles did not exhibit any particular tendency to be consistently lower or higher than observed wind speeds, but errors were generally higher than those given by persistence as a forecast. Figure 10 is an example. Experiment-2 forecasts appeared to result in lower average errors than Experiment-1 forecasts for 50 to 10 mb for all forecast intervals, although the error at 100 mb was higher in Experiment 2 for 24- and 36-hr forecasts (see Table 12). The cause of this result was not readily apparent, but there is doubt that one would achieve the same result using a large data sample.

At tropospheric levels, the forecast wind profiles usually indicated correctly the mandatory constant pressure surface at which the maximum wind speed occurred; however, the maximum wind speed was predicted to be higher than observed for

TABLE 11
TEMPERATURE FORECAST ERRORS* (100–10 mb)

(a) Experiment 1 (500-, 300-, and 200-mb prognostic charts)

Forecast length (hr)	Pressure level (mb)	Max. error	Persistence	Min. error	Persistence	Avg. error	Persistence
12	100	4.7	5.5	0.8	0.1	2.3	2.4
	50	2.5	3.6	1.1	0.3	1.7	2.2
	30	4.6	3.3	0.7	0.1	1.8	1.3
	10	4.6	5.0	0.1	0.6	2.4	2.8
24	100	4.8	6.9	1.1	0.1	2.2	2.3
	50	5.1	3.8	0.8	0.6	2.9	2.3
	30	7.4	4.7	0.1	0.5	2.8	2.5
	10	4.1	5.9	0.0	1.7	2.2	2.9
36	100	4.0	6.1	0.2	0.3	1.8	2.4
	50	6.3	5.6	0.9	2.0	3.1	3.3
	30	5.0	5.8	0.1	0.7	2.3	2.9
	10	1.8	2.7	1.4	2.7	1.6	2.7

(b) Experiment 2 (500-mb prognostic charts)

Forecast length (hr)	Pressure level (mb)	Max. error	Persistence	Min. error	Persistence	Avg. error	Persistence
12	100	5.2	5.5	0.8	0.1	2.3	2.4
	50	2.6	3.6	1.2	0.3	1.7	2.2
	30	4.6	3.3	0.6	0.1	1.8	1.3
	10	4.6	5.0	0.1	0.6	2.4	2.8
24	100	5.8	6.9	0.6	0.1	2.0	2.3
	50	5.2	3.8	0.9	0.6	3.0	2.3
	30	7.5	4.7	0.1	0.5	2.8	2.5
	10	4.2	5.9	0.0	1.7	2.2	2.9
36	100	3.8	6.1	0.1	0.3	1.8	2.4
	50	6.4	5.6	1.1	2.0	3.0	3.3
	30	5.1	5.8	0.2	0.7	2.3	2.9
	10	1.7	2.7	1.7	2.7	1.7	2.7

*Errors are in |°C|.

TABLE 12
WIND SPEED FORECAST ERRORS*(100—10 mb)

(a) Experiment 1 (500-, 300-, and 200-mb prognostic charts)

Forecast length (hr)	Pressure level (mb)	Max. error	Persistence	Min. error	Persistence	Avg. error	Persistence	Avg. observed wind speed
12	100	12	6	2	1	5.3	3.6	15.6
	50	10	5	1	1	4.6	3.0	6.3
	30	12	7	2	2	6.1	4.5	4.3
	10	6	3	3	1	3.9	1.8	8.7
24	100	18	9	1	1	7.3	5.1	12.7
	50	18	5	1	3	9.4	3.5	10.1
	30	17	3	1	1	9.5	2.0	6.9
	10	13	5	2	0	6.9	4.3	8.7
36	100	25	15	1	1	8.0	5.7	12.9
	50	33	7	5	0	12.7	3.4	5.2
	30	35	8	3	3	14.4	5.1	3.8
	10	39	6	1	1	12.7	3.3	7.5

(b) Experiment 2 (500-mb prognostic charts)

Forecast length (hr)	Pressure level (mb)	Max. error	Persistence	Min. error	Persistence	Avg. error	Persistence	Avg. observed wind speed
12	100	10	6	1	1	5.2	3.6	15.6
	50	8	5	0	1	2.2	3.0	6.4
	30	11	7	2	2	4.6	4.5	4.3
	10	6	3	1	1	3.4	1.8	8.7
24	100	22	9	3	1	9.7	5.1	12.7
	50	15	5	0	3	7.1	3.5	10.1
	30	15	3	3	1	6.9	2.0	6.9
	10	6	5	2	0	4.6	4.3	8.7
36	100	26	15	2	1	11.7	5.7	12.9
	50	13	7	1	0	5.1	3.4	5.2
	30	14	8	1	3	5.5	5.1	3.8
	10	9	6	3	1	5.4	3.3	7.5

*Error are m sec^{-1}

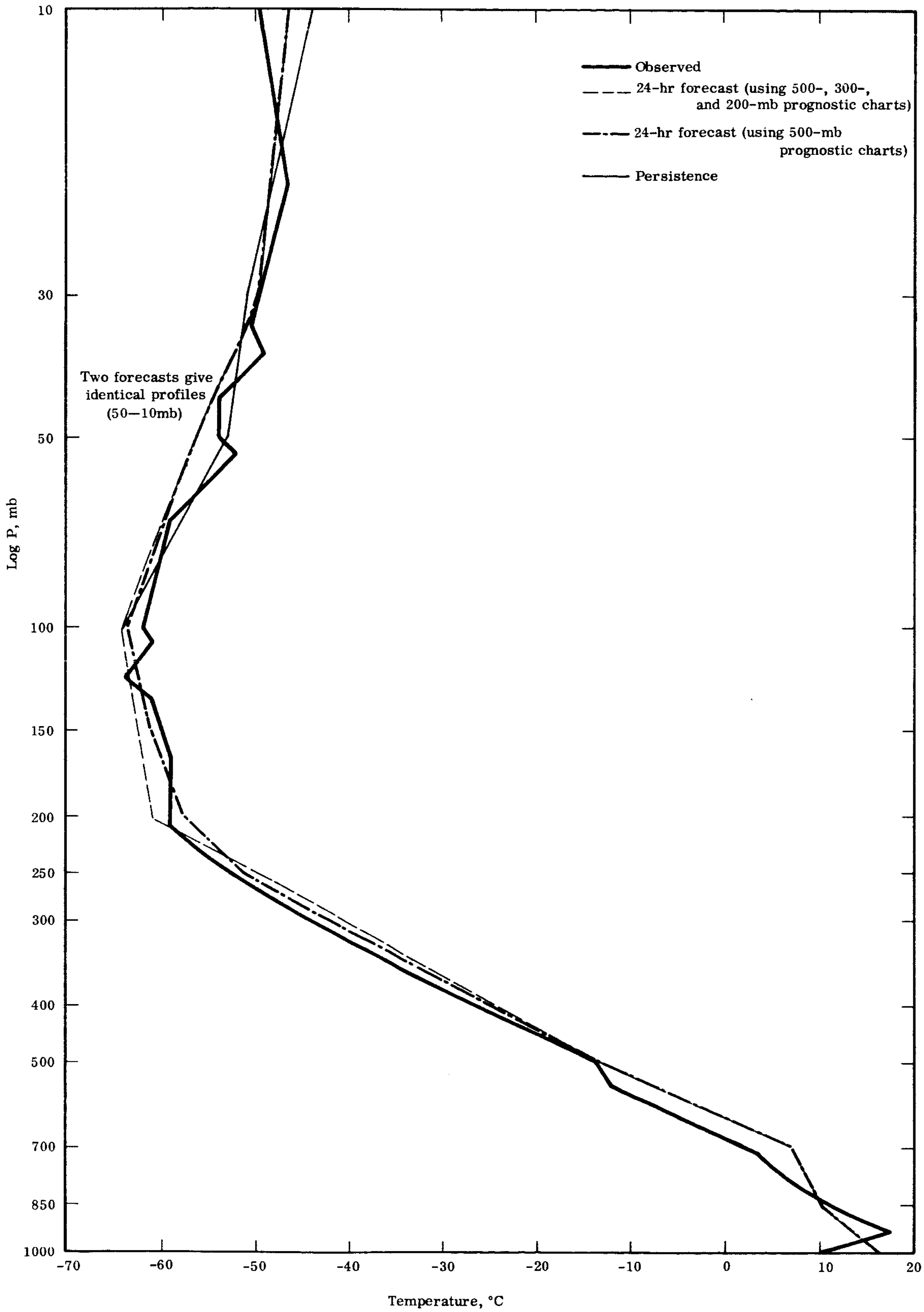

Fig. 9. 24-hr forecast and observed temperature profiles. Valid 12Z, 14 October 1965, Nashville, Tenn.

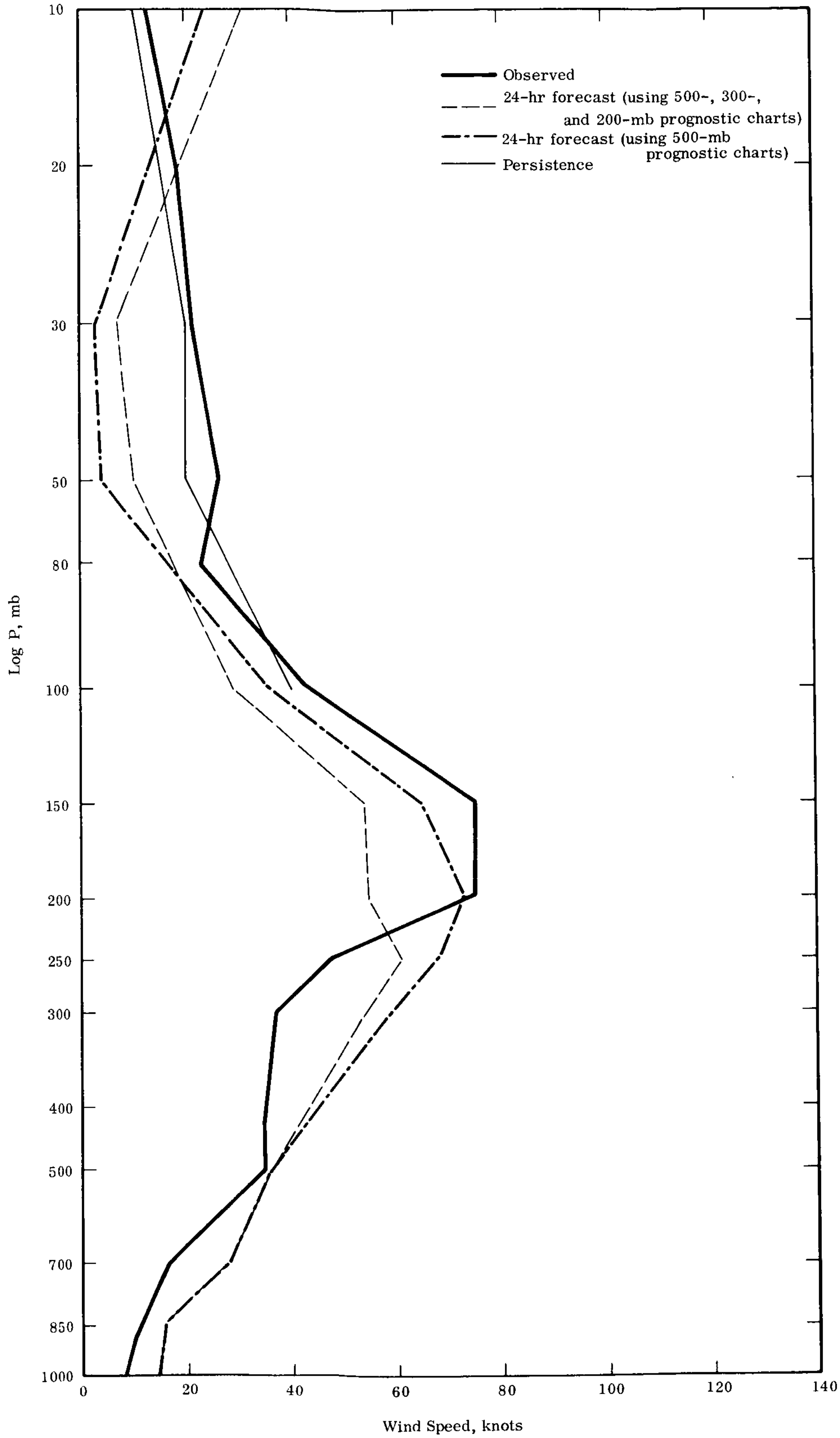

Fig. 10. 24-hr forecast and observed wind profiles. Valid 12Z, 13 October 1965, Nashville, Tenn.

several of the cases in the sample. The maximum wind speed is often located between constant pressure surfaces, a situation that is not specified by this forecast procedure.

The semi-obejective profile forecast procedure and the results of sample forecasts were evaluated with respect to NASA/MSFC operational problems. The products from the technique are obviously not applicable to the toxic-fuel diffusion problem.

With regard to sound propagation, the major limitation of the profile forecasts is that the variables, temperature and wind, are specified only at the surface and at mandatory constant pressure surfaces (850, 700, and 500 mb; i.e., 1.5, 3, and 5.5 km). Accurate sound profile and ray-tracing forecasts require greater definition than is given by these forecasts. Also, low-level temperature inversions (surface to 1.5 km) were not forecast very well. It is concluded that this forecast technique is not useful for sound profile forecasts.

For vehicle launch and design, considering the results of the evaluation of jet-stream prediction techniques (Section II D), it would be more advantageous to use a level of maximum wind modeling technique in conjunction with constant-pressure-surface prognoses than it would to use the constant pressure prognoses alone (as in the technique evaluated in this section). For stratospheric levels, persistence is generally at least as good as the technique being evaluated for 12- and 24-hr forecast intervals. This is true for winds in the fall-season data sample used, but results may be different with a data sample for winter, when more significant changes occur at stratospheric levels.

III. SUMMARY OF EVALUATION STUDIES

To perform a meaningful analysis of the evaluation study, one must keep in mind the specific forecast system of interest. In the situation evaluated here, the system consists of field stations manned by a small professional staff with access to: (a) centrally-prepared analyses and prognoses via facsimile and teletype, (b) conventional observations via teletype, and (c) special observations at the field forecast office locations. In addition, these field forecasters have high speed electronic computers available for use.

The first phase of the evaluation was directed toward establishing the adequacy of the centrally-prepared products in meeting the operational requirements of NASA/MSFC. This phase points up the magnitude of the "tailoring" task facing the field forecaster.

The second phase of the evaluation was concerned with assessing, where possible, some operational profile forecasts prepared by the field forecaster. Also included in this phase was an examination of the approaches of the various objective techniques to ascertain their usefulness relative to NASA/MSFC operational requirements.

The analysis of the various objective prediction techniques also afforded some insight into the possibility of predicting the small-scale features of profiles. The results of the evaluation are summarized below.

A. Adequacy of Current Centrally-prepared Products

The evaluations reported in Sections II A and II D, and in the literature cited, indicate: (a) that profile predictions obtained from centrally-prepared products are useful, but do not adequately meet the user requirements considered in this study, and (b) that considerable "tailoring" of these centrally-prepared products is required by the field forecaster. Specific problem areas are outlined below.

Vehicle Launch and Design

Straightforward inferences from multi-level dynamic predictions of important wind- and temperature-profile parameters in the vicinity of the level of maximum wind have some undesirable characteristics. First, the predicted magnitude of the maximum wind is, on the average, seriously underestimated. This bias is especially noticeable for the cases where the observed maximum wind is in excess of 45 m sec^{-1}.

The presently-available vertical resolution leads, not surprisingly, to serious discrepancies between observed and predicted vertical shears.

Sound Propagation

The winds-aloft and temperature forecasts (NMC FD's) contain inadequate vertical resolution to derive a detailed speed-of-sound profile for use in the NASA/MSFC ray-tracing model.

Diffusion

The centrally-prepared products yield only general guidance information to a field forecaster charged with furnishing predictive meteorological input to the present diffusion model in use at Cape Kennedy.

B. Potentially-useful Approaches to the Profile Prediction Problem

In addition to evaluating the available operational forecasts, we examined potentially-useful approaches that could lead to the development of automated forecaster aids. The results are discussed below.

Vehicle Launch and Design

For the important region in the vicinity of the jet stream, a physical-statistical modeling technique yielded 24-, 36-, and 48-hr forecasts of the LMW wind velocity that were considerably better than persistence or predictions obtained directly from the numerical models. An indirect comparison of the modeling forecasts with a sample of operational forecasts indicates that the objective procedure for predicting maximum wind velocity is, at the very least, competitive with the subjective techniques. The prediction of vertical shear was not satisfactory for any of the methods tested. However, the modeling approach holds promise if the predictand (vertical shears) is reformulated in terms more meaningful to the specific operational requirements of interest, and if more precise observations of the redefined predictand are employed when developing the required modeling predictor—predictand relationships.

For levels in the stratosphere, results reported in the literature [30] indicate that a physical-statistical prediction model can yield predictions superior to persistence for forecast periods up to 48 hours.

Sound Propagation

An analysis of the prediction of wind and temperature profiles in the planetary boundary layer, made with a physical-numerical model, revealed promising results. The vertical resolution of the predicted profiles is more compatible with the operational requirements than are other methods investigated. For some locations where the observational network is inadequate for the employment of a physical-numerical model, statistical methods would have to be substituted.

Analysis of a sample of operational, subjective 6-hr forecasts prepared by NASA/MSFC personnel indicated that, in general, operational requirements were satisfied. However, there were instances where the forecast evaluation indicated errors in the associated sound-propagation forecasts.

Diffusion

Of the prediction techniques investigated, the planetary boundary-layer prediction models show the most promise for use in toxic fuel diffusion prediction. The present diffusion "prediction" equation in use at NASA/KSFC uses real-time data to estimate the diffusive potential of the atmosphere and, therefore, is in reality a diagnostic equation. A prediction of diffusive potential, however, may be hampered by the inability to predict accurately the meteorological variables in the equation. A study evaluating the predictability of possible diffusion parameters is required to aid the designers of a diffusion prediction model.

C. The Potential of Predicting Small-scale Profile Features

An analysis has been made by Reiter [37] using AN/GMD 1 observations collected in the United States and southern Canada during February and March 1954. He showed that significantly different wind profiles are obtained by examining: (a) the originally computed sounding, (b) a smoothed profile, and (c) coded teletype data, and by changing the location in the vertical of the standard reporting levels.

A more recent publication [17] has given the accuracy of upper-air data obtained from AN/GMD 1 and AN/GMD 2 RAWIN sets at the Air Force Eastern Test Range. The pertinent figures given were that if the magnitude of the mean vector wind from the surface to 12.2 km was in the 15 to 30 m sec^{-1} range, the vector rms error of the observed wind at 12.2 km is 7 m sec^{-1}. If the mean vector wind is in the 30 to 45 m sec^{-1} range, which would be the case with a strong jet stream present, the observed error at 12.2 km increases to 15 m sec^{-1}. If the wind speed at 12.2 km was 75 m

sec^{-1}, a 20% error results; if the wind speed at this level is 60 m sec^{-1}, the error is 25%. Obviously, possible errors of this magnitude are not inconsequential. They will result in a certain degree of error being incorporated into a wind-profile prediction, because any subjective or objective forecast technique is highly dependent on initial-state conditions. Further, verification of prediction results is complicated by observational error.

More accurate wind-profile observations are now available at KSFC. This allows more accurate definition of profile parameters; prediction experiments outlined in Section IV will yield quantitative measures of the increase in predictability resulting from the employment of more accurate initial conditions.

The evaluation studies carried out afforded some insight into the feasibility of incorporating into prediction techniques the information contained in more accurate and more frequent profile measurements. Evaluation of the LMW modeling technique indicates that models developed from sub-synoptic scale observations of the jet stream can be employed to reduce the bias in dynamical wind predictions in the vicinity of the jet stream.

Prediction experiments, employing planetary boundary-layer models that simulate important sub-synoptic physical processes, have demonstrated the capability of predicting changes in the small-scale vertical structure of the wind and temperature fields. Further studies employing special observational samples are needed to firmly establish the degree to which parameterization techniques can depict small-scale structure of wind and temperature fields.

IV. TECHNIQUE DEVELOPMENT PLAN

In formulating a meaningful Technique Development Plan to improve the state of the art of profile prediction, it is necessary first to consider the future plans that will result in changes to the output from centralized automated weather centers. Two major programs of considerable importance are presently being conducted by the meteorological community. First, research is being conducted on a broad front and will likely lead to the implementation of more sophisticated dynamical prediction models. It is anticipated that the introduction of a primitive equation model at NMC in the near future will yield forecasts of the large-scale circulations that give greater vertical definition. Second, the implementation of the World Weather Watch [36] holds great promise for realizing more complete global observational coverage. This, plus the evolution of the dynamic prediction models, will lead to greater accuracy in forecasting the large-scale hemispheric circulation for periods out to 72 hours. However, it is highly unlikely that these improvements will, by themselves, yield entirely satisfactory results for the operational needs considered in this study. Thus, it seems that in the immediate future the field forecaster will be faced with the problem of combining the information contained in the output of the centralized forecasting units with standard observational information, as well as with the information obtained from special "on-site" observations. The primary objective of formulating a Technique Development Plan is the utilization of automated techniques to assist the field forecaster in synthesizing the vast quantity of information at his disposal so that he may obtain operationally useful profile predictions.

In formulating the Plan, valuable clues were obtained regarding the various approaches derived from the evaluation phase of this study. In addition, TRC scientists who have been deeply involved in similar technique development efforts with the U.S. Air Force and U.S. Weather Bureau were consulted. The Technique Development Plan has been designed to take advantage of the unique observational capabilities of the research and development sites of interest. Another important general feature of the Plan is that, for each study proposed, careful consideration will be given to the definition of the predictand such that it will be expressed in the most useful terms for the operation it supports. The Plan is subdivided into three projects generally conforming to the three operational problem areas outlined by NASA/MSFC.

Project I is concerned with upper-tropospheric and stratospheric prediction. The aim here is to obtain accurate profile predictions in the vicinity of the jet stream which, of course, are critical for vehicle launch operations.

Project II is concerned with the development of lower-tropospheric profile predictions. The goal is to provide better vertical definition in the predictive profiles, mainly in the support of the sound propagation problem, but also to attempt to provide useful information for the prediction of the diffusive potential of the atmosphere.

Project III is concerned with diffusive parameter prediction. The objective is two-fold. First, methods will be developed to predict the parameter required for currently-employed diffusion models. Second, an assessment will be made of the relative predictability of a larger set of possible diffusion parameters to guide the development of more sophisticated diffusion models.

A. Project I: Upper-tropospheric and Stratospheric Prediction

The primary emphasis here is to develop techniques that yield more accurate wind-profile predictions in the vicinity of the level(s) of maximum wind. The project is subdivided into three tasks.

Task I.1: Physical-statistical Prediction of Wind Profiles

The objective is to develop prediction techniques for the wind profile in the vicinity of the LMW. Prediction techniques will apply to the southeastern U.S., and the primary zone of interest will extend from 10 to 16 km. The forecast interval will initially be 0—48 hours.

Statistical methods will be employed to combine predictive information from several sources to yield prediction equations for salient features of wind profile. The predictands will include the magnitude of the wind speed at the LMW, height of the LMW(s), shears above and below the LMW(s), the thickness of the "layer" of maximum wind, and the probability of exceeding special "threshold" values of these parameters.

In developing prediction equations, the profile parameters will be specified where possible from the FPS-16 Radar/Jimsphere Wind Data.

The sources of predictive information to be considered are:

(a) centrally-prepared multi-level numerical predictions,

(b) analyses of conventional meteorological observations, and

(c) special high-resolution "on-site" observations.

For short-range predictions (0—12 hours) emphasis will be placed on using, as predictors, initial conditions and time changes of these initial conditions derivable from the conventional and special observations.

A large number of possible predictors will be considered in the derivation of the prediction equations. These predictors will be derived not only from observations at the predictand station, but from observations at a network of stations in the vicinity of the predictand station.

The necessary reduction of the number of predictors to be used in the actual prediction equations will be done objectively by statistical screening methods [25, 26]. The predictor—predictand relationships will be derived statistically. There is a choice of methods but, for the most part, regression techniques will be used [25]. However, if estimates of the probability of exceeding certain threshold values of the predictand are operationally useful, an analysis of the same developmental sample by the REEP (Regression Estimation of Event Probabilities) technique will be made. The feasibility of this approach was established by Ball [2].

For the longer forecast periods (out to 36—48 hours), the approach will be similar, but greater emphasis will be placed on utilizing the predictive information contained in centrally-prepared multi-level dynamical predictions. Here the work of Reiter [37] and Spiegler [39] will be extended. Salient features of the wind profile such as height(s) of the LMW(s), magnitude of the maximum wind, thickness of the layer of maximum wind (LRMW), and the associated shears will be related to the output of multi-level dynamical predictions. The derived specification equations, when applied to prognoses, will yield a mapping of the LRMW parameters.

A second step in this approach will be to further refine the estimates of profile parameters by employing modeling techniques. Earlier experiments by Spiegler [39] have shown that there is a tendency for existing dynamical models to underestimate the magnitude of the wind speed in the vicinity of the axis of the jet stream. Spiegler further demonstrated that this bias can be reduced by employing a jet-stream model similar to that of Endlich [6]. The modeling technique takes into account the structure of the wind field in the vicinity of the jet core, and leads to an improved estimate of the wind field at the jet-stream level.

Task I.2: Prediction of Wind and Temperature Profiles

The objective is to develop a wind and temperature prediction technique for the stratosphere. This technique will be applicable to the southeastern U.S. and will yield temperature and wind predictions for the 100-, 50-, and 30-mb levels. Initially, the forecast period will be 0—36 hours.

A physical-statistical prediction model developed by Ostby, Veigas, and Erickson [30] will be extended to optimize its usefulness in support of launch operations. The present model utilizes a predictor grid centered at the predictand station. Two classes of predictors are employed in this model; one is dynamic predictions of tropospheric circulation parameters, and the other is analyzed parameters in the stratosphere and time changes of those parameters.

A test on independent data indicated that the model yielded predictions superior to persistence for both the 24- and 48-hr forecast intervals [30]. In modifying the technique, emphasis will be placed on minimizing the errors in gradients rather than on minimizing the errors in the height field.

Task I.3: Development of a Synoptic Climatology of Wind and Temperature Profiles

The objective is to test the feasibility of the decision-tree approach to generate a synoptic climatology of wind and temperature profiles. Initially, operationally-important LMW parameters will be studied. If the feasibility study proves successful, the work could be extended to include profile parameters of importance to sound propagation. The prediction period of interest extends to 72 hours.

The principle difficulty in deriving a synoptic climatology that is more meaningful than conventional climatology is that there is almost countless criteria that could potentially serve as a basis for subdividing a sample into a series of types. Further, a given set of types may prove to be an effective predictor for one parameter, but rather useless for another.

To alleviate these problems, a computerized decision-tree framework is suggested so that a number of criteria may be tested. A series of stratifying criteria will be tested and the relative frequency of occurrence of categorized profile parameters will be computed and compared with conventional climatological relative frequencies. In this fashion, numerous stratification criteria and their order of application can be tested in an efficient manner. If the study is successful, a better 48–72-hr climatology for LMW parameters will be available to the field forecaster.

B. Project II: Lower-tropospheric Prediction

The most significant shortcoming of the profile forecasts in the lower troposphere that are readily available to the field forecaster is the lack of vertical resolution in profiles derivable from centrally-prepared prognostic charts.

Two approaches are recommended to overcome this deficiency. The first is to develop physical and physical-statistical models capable of directly producing profiles of wind and virtual temperature. The dual development of models is recommended because observational requirements for a physical model may not be met for all locations, e.g., coastal sites.

The second approach is to develop a series of automated aids that can be employed on an "on call" basis to assist the field forecaster in establishing the time evolution of the synoptic situation, which in turn will aid in making inferences of time changes in the wind and virtual temperature profiles.

Task II.1: Observational Requirements for Planetary Boundary-layer Models

The objective is to provide the necessary guidance information to decide which, if either, of the planetary boundary layer (PBL) models discussed in this report should be implemented in support of sound profile prediction for static test firings.

The initial approach will be to present to MSFC scientists, who are knowledgeable of future meteorological requirements, a summary of the observational requirements of the two models, the length of the useful forecast period, and the accuracy potential of both models. If such a technical exchange cannot provide sufficient information to determine the relative suitability of the two models, the next step will be to design experiments, using existing special observational networks, to provide the required information.

Task II.2: Development of a Physical Planetary Boundary-layer Model

The objective is to develop a physical prediction model that yields wind and virtual temperature profiles in the lower 2 km of the atmosphere. Both of the two possible approaches are physical atmospheric models that include processes such as eddy fluxes of heat and vapor, the transport of heat and vapor by horizontal winds, the influence of terrain- and friction-induced vertical motions, and the heat and mass exchanges involved in water-substance phase changes.

The developmental mathematical formulation on both models has reached a point where work on the required set of programs for an implementable "base technique" could be initiated. The prime difference between the two models is that one uses observations from a conventional meteorological network, while the other requires augmentation of these observations from a sub-synoptic scale observing system.

Task II.3: Development of a Physical-statistical Prediction Model

The objective is to develop and test a prediction technique for the wind and virtual temperature profiles between the surface and 6 km, in support of sound profile predictions. The techniques developed will be applicable to the three test sites of interest. Prediction intervals will initially extend to 36 hours.

Profile prediction relationships will be derived by the method of screening regression. Predictors will be selected from three sources:

(a) Detailed analyses of the wind and temperature of a three-dimensional array of grid points over the southeastern U.S. The horizontal and vertical spacing of the grid array will be compatible with the available observational data;

(b) Special "on-site" rawinsonde observations taken at frequent intervals prior to forecast time;

(c) Multi-level prognoses for 850, 700, and 500 mb.

The predictands, and the wind and virtual temperature profiles, will be formulated in several ways. One alternative would be to derive prediction equations for the change in virtual temperature for each of several levels within the layer of interest. Another alternative would be to represent the predictand profile by a curve-fitting technique and to derive prediction equations for the fitting coefficients. This would permit a forecast of the complete profile. Multiple formulations of the predictand are recommended, because the added cost is slight and it is not obvious which of several possible formulations will lead to the best results when the predictions are used as input for specific operational problems, e.g., sound propagation predictions.

Task II.4: Development of "on call" Objective Forecast Aids

The objective is to provide a series of objective automated aids that could be employed at the discretion of the field forecaster. These techniques will be applicable to the southeastern U.S.; initially, forecast periods out to 36 hours will be considered.

Multiple approaches are visualized for this task. The first step will be to outline specific objectives; this will be done jointly by the scientists responsible for the development of the aids and by operational personnel.

In general, the plan will be to isolate significant features of the circulation patterns and then to develop techniques to predict their behavior. As an example, there are occasions when an approaching cyclone will dominate the sequence of weather at a given field station. In this case, prediction methods for the displacement and change in intensity of the cyclone could prove to be of valuable assistance.

A series of techniques which might be considered for implementation as aids is:

(a) Prediction of the displacement and change in intensity of cyclones and anti-cyclones: These techniques have already been developed and tested [28, 29]. They have been automated and are used operationally at the Travelers Weather Service.

(b) Prediction of the behavior of fronts: Development along the lines of the cyclone prediction experiments are recommended. That is, predictors would be defined in a moving coordinate system fixed with respect to the location of the surface frontal position. Frontal motion and associated characteristics would then be related to meteorological parameters analyzed over the moving coordinate predictor grid.

(c) Prediction of low-level (launch) winds: Russo, et al. [38], in a statistical prediction experiment, produced results superior to subjective 7-hr forecasts of the surface wind. A possible aid could be developed along similar lines, where winds are related by statistical techniques to parameters measured over a meteorological network in the southeastern

U.S. The output of this technique could be in terms of the probability of occurrence of operationally-important categories of wind speed and/or direction. Parameters derived from both special observations and centrally-prepared products would be considered.

(d) Prediction of cyclogenetic tendencies: Experimental application of the cyclone change-in-intensity equations indicate that it may be feasible to develop a technique to delineate areas where cyclogenesis is probable.

C. Project III: Diffusion Parameter Prediction

Two tasks are recommended for this project. First, the predictability of the meteorological parameters currently used in the operational diffusion equation must be established as a function of forecast interval. In addition, there is a need to establish the relative predictability of additional meteorological parameters that might be considered for inclusion in future diffusion models. Such results should provide valuable guidance for those involved in developing more sophisticated diffusion models.

The second task is to develop techniques for predicting the development and dissipation of a significant profile feature—the low-level inversion.

Task III.1 Establishment of the Predictability of Possible Diffusion Parameters

The objective is to derive prediction equations for the parameters presently employed in the operational diffusion model [16], and to establish the relative predictability of a more comprehensive set of possible diffusion parameters. This will provide guidance to researchers developing more sophisticated diffusion models for implementation into a diffusion prediction system.

From a survey of the literature and consultation with scientists (at TRC and at NASA/MSFC localities) possessing strong capabilities in diffusion meteorology, a list of parameters will be drawn up that are thought to be related to the diffusion process. This list will include variables obtainable from both routine and special observations.

The predictability obtained from statistical prediction experiments will be used to establish the first estimate of the relative predictability of the various parameters considered. Interrelationships between the various prediction errors will be established so that an analysis of the impact of prediction errors on a multi-parameter diffusion model may be analyzed.

The predictability study will yield prediction equations for input to the present operational diffusion model.

As a control, results obtained from the predictability experiments will be compared with those obtained from subjective methods, as well as with those of physical prediction models.

Task III.2 Prediction of the Development or Persistence of Low-level Temperature Inversions

The objective is to develop a technique to predict categories of low-level temperature profiles for the three NASA/MSFC test and launch-site locations.

The occurrence of marked stability in the planetary boundary layer creates atmospheric conditions that are often very unfavorable for the dispersion of sound and the diffusion of toxic vapors. The frequency of serious problems is clearly a function of a particular location (local effects), time of day, season of year, and synoptic situation.

In this forecast problem (as in many others), there are numerous instances when a highly reliable forecast can be made. For example, during daylight hours after the passage of a rapidly moving strong cold front, relatively unstable conditions can be expected. On the other hand, at night under conditions of very light wind speed and strong radiation cooling, very stable lapse rates are found in layers immediately adjacent to the surface.

There are, of course, many situations where the forecasting problem is much more difficult. For this reason, a two-step approach is proposed. The first step consists of asking and answering a series of questions (within a decision-tree framework) that will account for those cases (situations) where highly reliable prediction statements can be made from current data. The remaining cases will be dealt with statistically by using the REEP technique [26] to derive equations that yield the probability of occurrence of categories of sounding lapse rate. In the formulation of operationally significant categories, previous work accomplished under this contract and by other investigators [12] will be utilized. The decision-tree—REEP approach has been used successfully in a similar manner to diagnose upper-level humidity from surface-synoptic station data [2, 3].

In the development of the decision-tree and REEP prediction relationships, the following types of predictors will be considered:

(a) local climatology

(b) season of year

(c) time of day, both of initial-state data and of valid forecast time

(d) synoptic situations

(e) surface data and low-level temperature profile.

An extensive amount of research has been accomplished by Eastern Air Line personnel in solving various forecasting problems in the southeastern U.S. Techniques developed for the prediction of such phenomena as fog and stratus, as reported by George [13], may have application (with modification) to the inversion prediction problem. Where possible, use will be made of this and other previous research, particularly in the decision-tree phase of the technique development.

Items (a)—(c) above reflect the sensitivity of temperature inversion occurrence to local and adjacent terrain and to diurnal and seasonal variations. However, it is well-known that, given the suitable atmospheric conditions [Items (d) and (e)], inversions may develop or persist almost regardless of location, time of day, or season of year. Whether a partially or wholly separate set of relationships should be developed for each of the three NASA/MSFC sites would be determined from a detailed examination and analysis of the data.

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APPENDIX A

DESCRIPTION OF WINDS-ALOFT FORECAST PROCEDURE AND INHERENT ERRORS [1]

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APPENDIX A. DESCRIPTION OF WINDS-ALOFT FORECAST PROCEDURE AND INHERENT ERRORS [1]

A.I. Technique

Forecasts are obtained by using the information that is routinely available from NMC's 3-level baroclinic model. This model generates forecasts (out to 36 hours) of stream functions (ψ) (from which winds can be obtained) and D-values (departures from standard atmospheric height) at three constant pressure surfaces—850, 700, and 500 mb. Regression equations have been developed for interpolating in the vertical for determining ψ and temperature at the levels not directly obtained from the 3-level model. Because the forecasts are at grid points, a second interpolation is necessary to obtain values at stations.

A.II. Errors

Errors inherent in the numerical FD forecasts are grouped into three main categories:

(a) Errors due to the computer process—These are basically truncation errors and result from the necessary use of finite-difference approximations instead of exact differentials;

(b) Errors associated with the analysis process—Observed data (which is used for obtaining the analyses, which in turn are used as initial data for the forecasts) is interpolated from actual station locations to the surrounding grid points. The "linear interpolation could result in reduction of resolution" [1];

(c) Errors resulting from the forecast model—The major problem is that the NMC 3-level baroclinic model tends to underforecast the amplitude of troughs, especially in winter, and this is responsible for most of the errors in the relatively data-dense U.S.

Additional sources of error are:

(a) the vertical interpolations and extrapolations that are necessary to obtain values of wind and temperature at the FD levels from the 3-level model. In performing these interpolations and extrapolations, a "severe assumption of essentially linear distribution of the

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stream function and D-values" [1] (from which the winds and temperatures are derived) is imposed;

(b) the development, in winter, of large errors in temperature from the downward extrapolation of temperatures from 800 mb, because "the regression equations do not account for the anomolous temperature curves with sharp inversions that occur" [1];

(c) interpolation to the station of grid-point values of temperature and u and v components of the wind results in reduction of resolution.

APPENDIX B

VERIFICATION TABLES FOR NMC WINDS-ALOFT FORECASTS

TABLE B-1
ROOT-MEAN-SQUARE ERRORS FOR 12- AND 24-hr FORECASTS OF WIND FOR JACKSONVILLE, FLORIDA*
(50 cases; 12 Z April 15—12 Z April 30, 1965)

Forecast length (hr)	Level (m)	Observed speed (m sec^{-1})	Forecast speed (m sec^{-1})	rms error: Vector wind (m sec^{-1})	rms error: Wind dir. (deg.)	rms error: Wind speed (m sec^{-1})
12	914	7.7	5.0	5.0	30	-2
	1524	7.7	5.5	4.5	30	-2
	3281	8.1	7.7	3.5	30	-0
	4268	13.0	12.0	4.5	20	-0.5
	6562	16.5	15.5	5.0	20	-0
	8086	20.0	21.0	7.0	10	+0
24	914	7.7	4.5	6.1	40	-3.0
	1524	6.6	5.0	5.0	50	-1.0
	3281	9.0	8.1	5.0	30	-0.5
	4268	13.5	11.5	5.6	30	-2.0
	6562	16.0	14.5	6.1	20	1.0
	8086	19.0	19.0	5.6	10	-0

*Nearest RAOB station to Cape Kennedy for which verification statistics were available.

TABLE B-2

ROOT-MEAN-SQUARE ERRORS FOR 12- AND 24-hr FORECASTS OF WIND FOR BURRWOOD, LOUISIANA*

(50 cases; 12 Z April 5—12 Z April 30, 1965)

Forecast length (hr)	Level (m)	Observed speed (m sec^{-1})	Forecast speed (m sec^{-1})	rms error		
				Vector wind (m sec^{-1})	Wind dir. (deg.)	Wind speed (m sec^{-1})
12	914	8.1	6.1	4.5	40	-2
	1524	7.2	6.6	4.5	30	-0
	3281	11.0	11.0	4.5	10	-0
	4268	14.5	15.0	4.5	10	+0.5
	6562	19.5	19.0	4.0	10	-0
	8086	23.0	23.0	5.0	10	+0
24	914	9.0	6.1	7.2	50	-2
	1524	7.7	6.6	6.1	50	-1
	3281	10.0	9.5	5.0	30	-0
	4268	12.0	13.0	4.5	20	+1
	6562	16.0	16.5	5.0	20	+0
	8086	21.0	21.5	5.5	10	+0

*Nearest RAOB station to Picayune, Mississippi for which verifications were available.

TABLE B-3
ROOT-MEAN-SQUARE ERRORS FOR 12- AND 24-hr FORECASTS
OF WIND FOR NASHVILLE, TENNESSEE*
(50 cases; 12 Z April 5—12 Z April 30, 1965)

Forecast length (hr)	Level (m)	Observed speed (m sec^{-1})	Forecast speed (m sec^{-1})	rms error		
				Vector wind (m sec^{-1})	Wind dir. (deg.)	Wind speed (m sec^{-1})
12	914	9.5	10.0	5.5	20	+0.5
	1524	10.5	11.5	5.0	20	+0.5
	3281	15.0	14.5	8.5	20	-0
	4268	19.5	18.5	7.7	10	-1.0
	6562	23.0	22.5	6.1	10	-0
	8086	26.0	26.0	7.1	10	+0
24	914	12.0	10.0	6.6	40	-2
	1524	12.5	11.5	6.6	20	-1
	3281	14.0	14.5	7.2	20	+0.5
	4268	17.5	17.5	6.6	20	-0
	6562	23.5	21.0	8.2	10	1.5
	8086	28.0	24.5	9.5	10	-3.0

*Nearest RAOB station to Huntsville for which verification statistics were available.

TABLE B-4
ROOT-MEAN-SQUARE ERRORS FOR 12-hr FORECASTS
OF TEMPERATURE AND WIND*
(60 cases)

Station	Level (m)	u (m sec^{-1})	v (m sec^{-1})	$\vec{V}$ (m sec^{-1})	Average observed speed (m sec^{-1})	T (°C)
Nashville	914	4.5	6.2	7.4	9.8	—
	1524	3.4	4.4	5.6	8.8	1.5
	2134	3.2	3.8	5.0	9.4	—
	3281	3.2	4.1	5.2	9.0	1.7
	4805	3.4	4.2	5.4	10.7	1.5
	6562	4.9	5.5	7.3	12.0	1.7
	8086	4.7	4.9	6.2	14.2	2.3
Miami	914	3.2	5.1	5.1	8.7	—
	1524	3.6	4.0	5.4	8.0	1.5
	2134	3.3	4.0	5.0	7.3	—
	3281	3.3	3.5	4.9	7.7	1.6
	4805	3.9	3.9	5.5	7.0	1.2
	6562	3.8	4.6	6.0	7.0	1.2
	8086	5.8	5.1	7.7	8.6	1.4

*u—west-east component of wind
v—south-north component of wind
$\vec{V}$—vector wind
T—temperature

APPENDIX C

SIMPLIFIED ACOUSTIC-RAY TRACING MODEL AS AID IN CATEGORIZING METEOROLOGICAL PROFILES WITH REGARD TO SOUND PROPAGATION

APPENDIX C. SIMPLIFIED ACOUSTIC-RAY TRACING MODEL AS AID IN CATEGORIZING METEOROLOGICAL PROFILES WITH REGARD TO SOUND PROPAGATION

The vertical profile of variables is defined incrementally by parameters of height (h), sound speed (s) in medium, and velocity ($\vec{v}$) of movement of the medium. Sound speed in the atmosphere is a function of temperature (T) and humidity.

The surface level (h = 0) parameters are designated by subscripts, h_0, $\vec{v}_0$, s_0, T_0. The next level would be h_1, etc. The general level is h_n, etc., and level h_m is defined as level h_{n-1}.

Symbol definitions:

- Θ Azimuth angle, radians
- Θ^* Azimuth angle of velocity shear
- ϕ Elevation angle, radians
- r Radial surface distance from source
- V Local maximum speed of sound relative to surface
- V_Θ Local speed of sound in direction Θ, relative to surface
- F Relative flux of energy intercepted and returned to surface
- I Intensity of return at surface by profile segment

Defined relationships:

$\vec{v} = x\vec{i} + y\vec{j}$; $\vec{v}$ defines the direction Θ

$V_m = |\vec{v}| + s = (x^2 + y^2)^{1/2} + s$

$V = |\vec{v} - \vec{v}_0| + (s - s_0)$; $\vec{v} - \vec{v}_0$ defines the direction Θ^*

$V_{m\Theta^*} = [(x_m \cos \Theta^*)^2 + (y_m \sin \Theta^*)^2]^{1/2} + s_m$

$dV = V_n - (V_m)_{\Theta^*_n}$: so defined for this development

$r = 2h \cot \phi_0$; an approximation to range where h is the critical height for ray ϕ_0

$(V_0)_\Theta = V_\Theta \cos (\phi_0)_\Theta$; Snell's law for ray with speed V at critical height

Developed relationships:

$\phi_0 = (2\Delta V/V_\Theta)^{1/2}$;	from cosine expansion and definitions; if V negative, ϕ_0 does not exist
$F = (\phi_0)_n - (\phi_0)_m$;	per azimuth angle of one radian; if zero or negative, does not exist
$I = \left\lvert \dfrac{1}{\dfrac{h}{\phi_0}\left[\dfrac{V_\Theta \phi_0}{dV_\Theta/dh} - \dfrac{h}{\phi_s}\right]} \right\rvert$	approximate proportionality; note ability to approach infinity
$SFL = 162 + 10 \log F$	Sound Flux Level, approximate normalization to source strength of one megawatt; does not exist if F does not exist
$SPL = 159 + 10 \log I$	Sound Pressure Level, approximate normalization to source strength of one megawatt; distances and heights in meters

The interval table describing the model should contain the following:

h, W/S, W/D, T*, s, x, y, V, V, Θ*, $V_{\Theta *}$, dV, ϕ_0, r, SFL, SPL.

Of these, the following should be output:

h, s, x, y, ϕ_0, r, SFL, SPL.

APPENDIX D

SAMPLE OF WIND PROFILES WITH POORLY DEFINED LMW

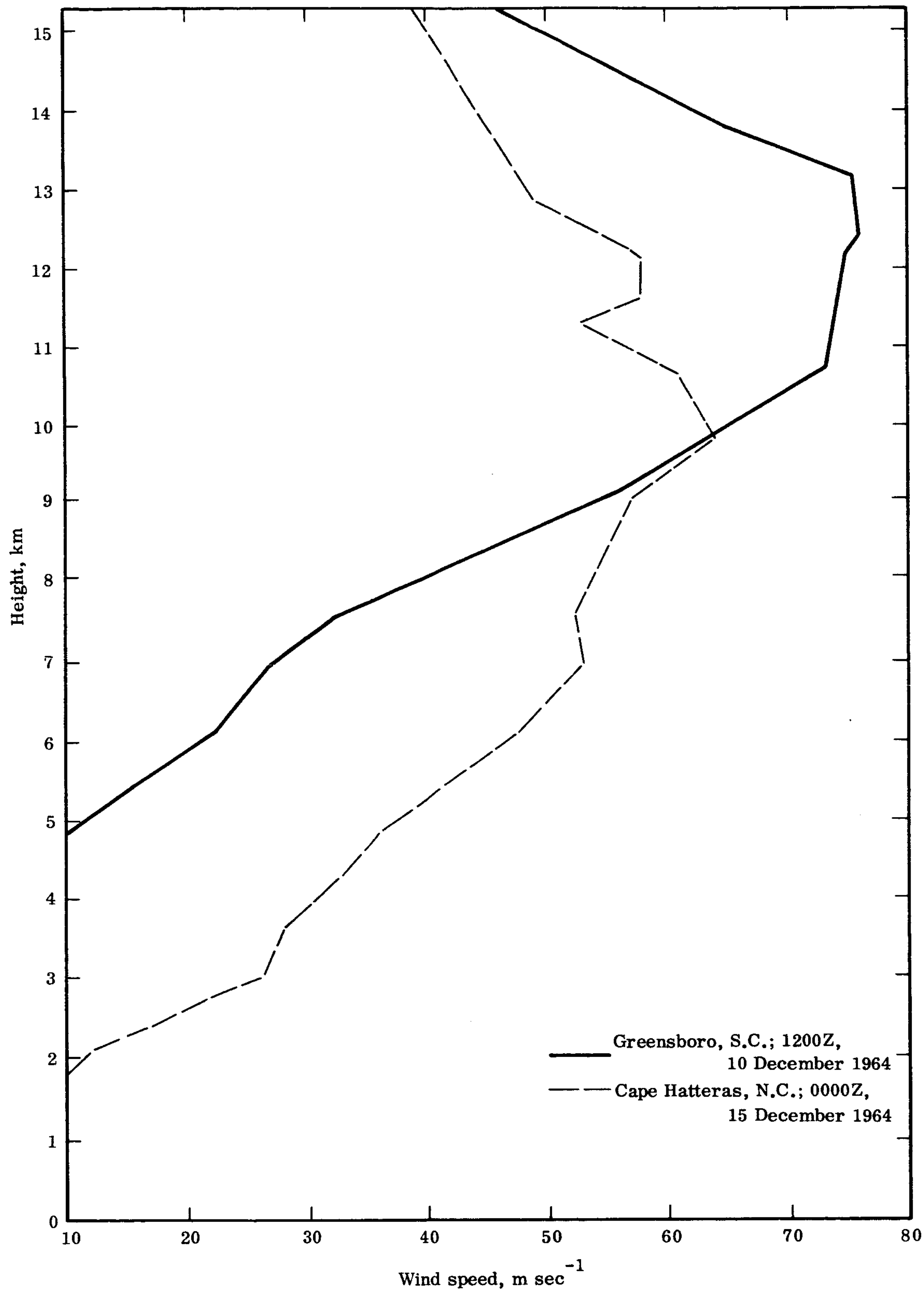

Fig. D-1. Broad layer of strong maximum wind.

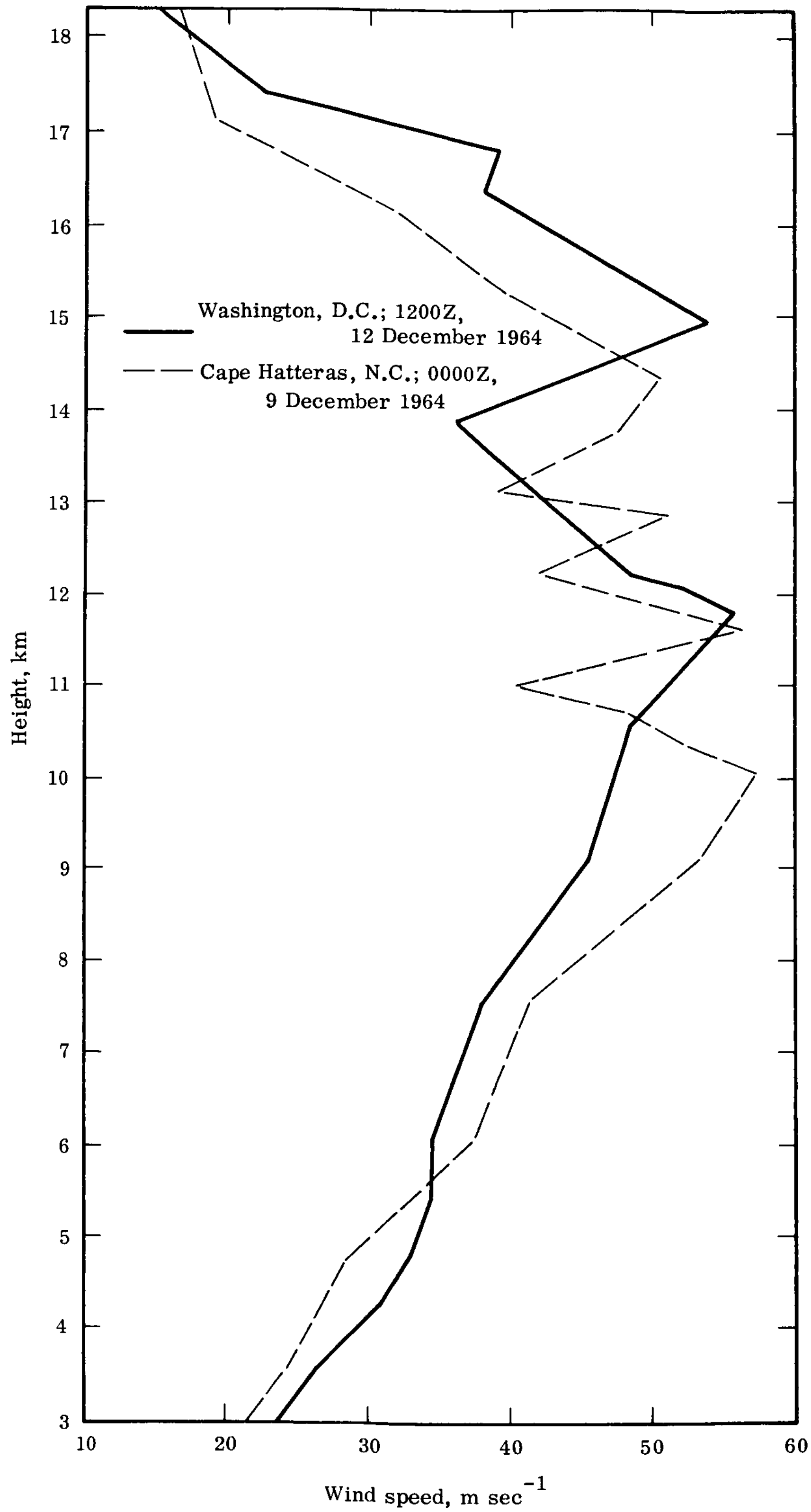

Fig. D-2. Distinct, strong, multiple layers of maximum wind.

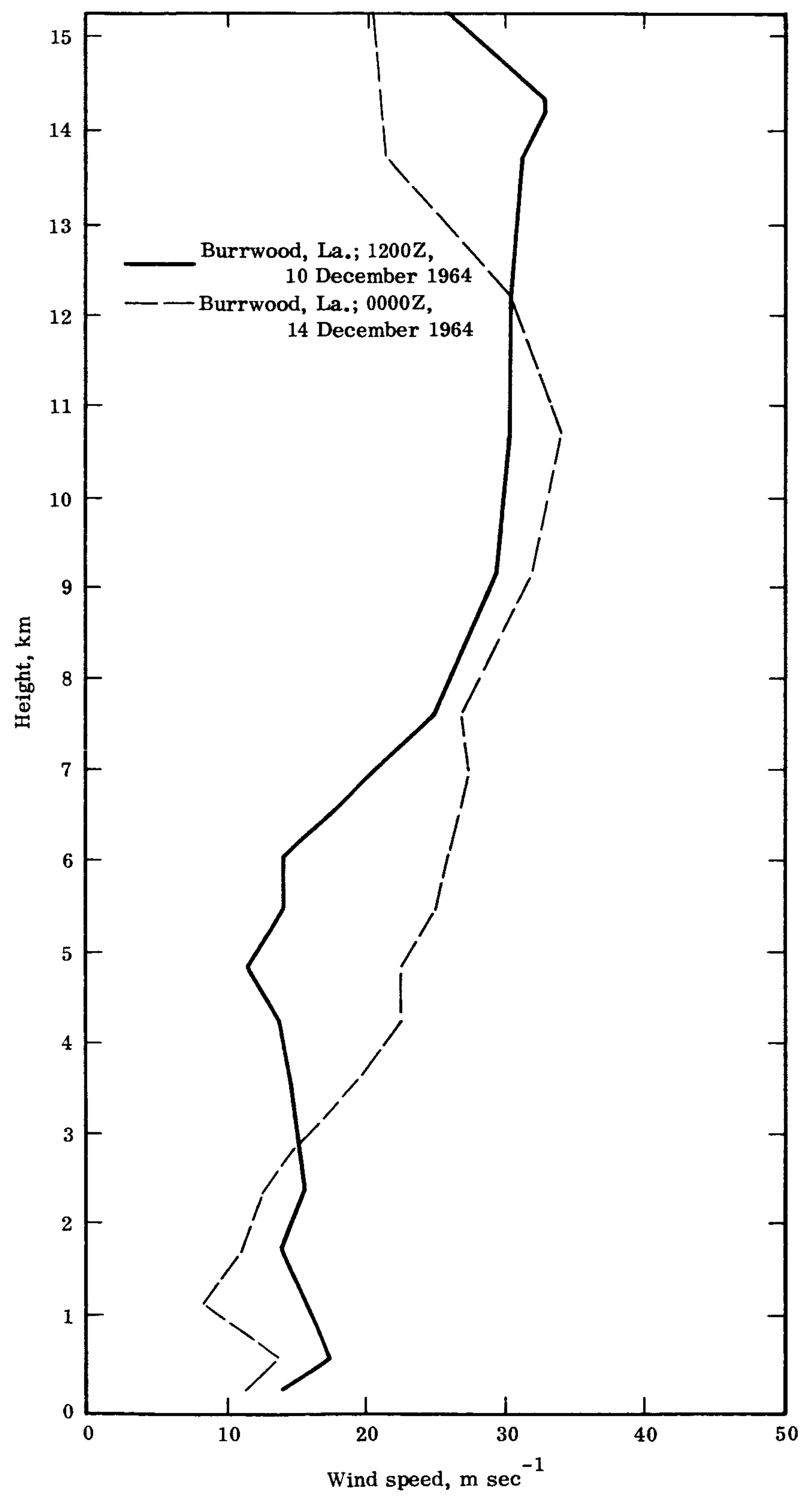

Fig. D-3. Broad layer of weak maximum wind.

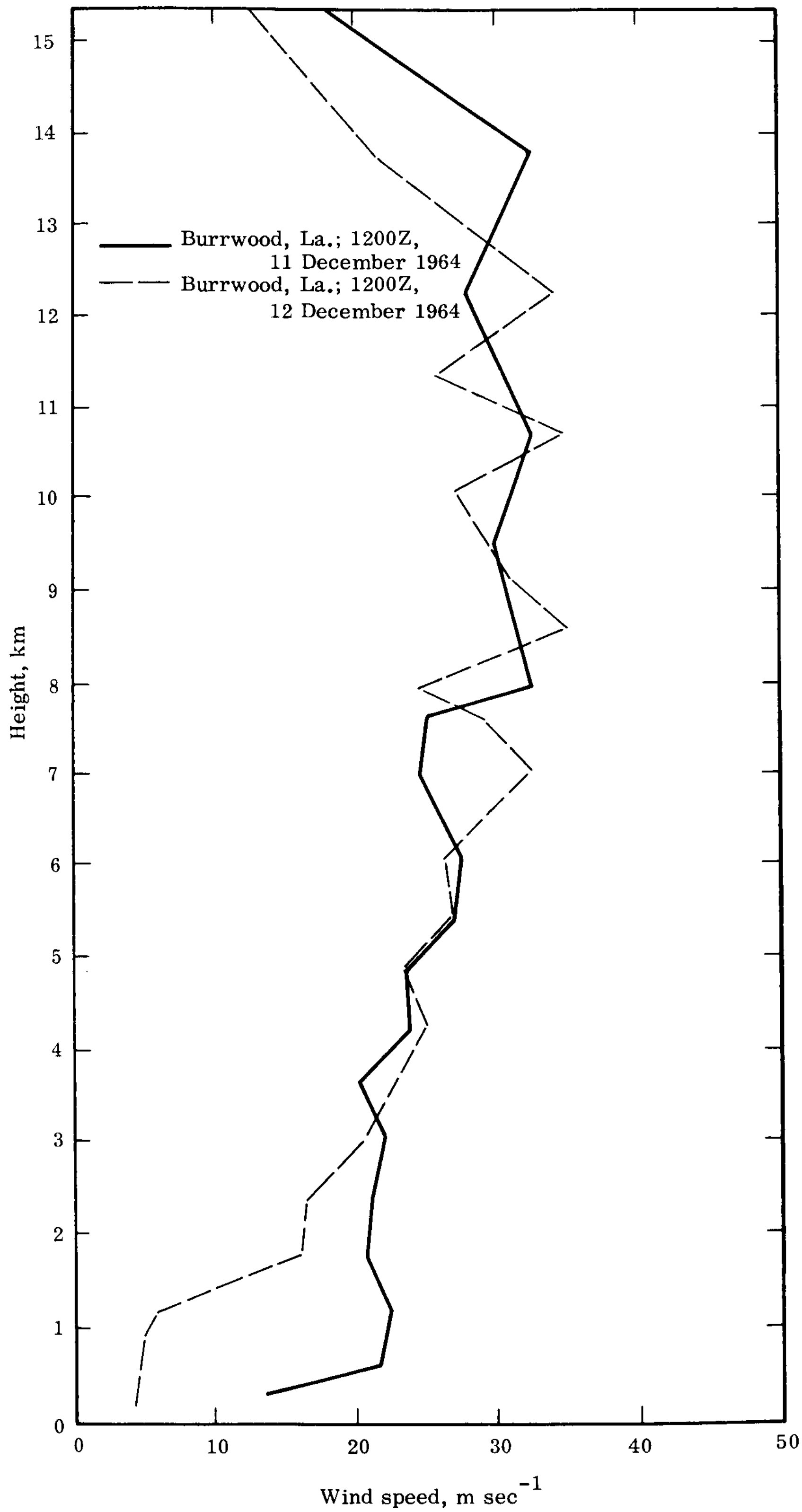

Fig. D-4. Weak multiple layers of maximum wind.

APPENDIX E

CONSTANT PRESSURE SURFACE FORECAST PROCEDURE (1000—10 mb)

APPENDIX E. CONSTANT PRESSURE PROFILE FORECAST PROCEDURE (1000—10 mb)

E.I Procedure for Generating 24-hr Forecast Profiles

Because there is more 24-hr prognostic constant-pressure-surface information available than at any other forecast time, the 24-hr forecast profiles were generated first. Wind speeds were computed using the geostrophic wind equation, which requires values of height at four points surrounding a station as input.

A program was written for the IBM 1620 computer which computes the heights, temperatures, and geostrophic winds for twelve constant-pressure surfaces for forecast periods of 12, 24, and 36 hrs for a selected station. The twelve constant-pressure surfaces are 1000, 850, 700, 500, 300, 250, 200, 150, 100, 50, 30, and 10 mb. In all forecasts, the 1000-mb height was determined from the surface-pressure analysis chart, surface-pressure prognostic chart, or from actual observed data for initial time, if available.

"Past" data fields of height and temperature for all experiments were read and tabulated for selected points from the set of twelve analysis charts for the initial or base time of the prediction procedure. Using the 24-hr NMC prognostic charts, values of height were read and tabulated for a set of corresponding points to obtain the height information necessary for the regression equations. Values of temperature at the base level are required input for the vertical extrapolation equations; the NMC prognostic charts do not include temperature fields. A simple trajectory method was used to obtain the forecast temperatures at the location of interest and at selected points. This method uses the initial and 24-hr forecast wind fields, and the initial temperature fields, to compute a forecast temperature field for the 1000-, 850-, 700-, and 500-mb pressure levels. The 24-hr, 300-, and 200-mb forecast temperatures for Experiment 1, obtained from Standard Atmospheric Tables using the forecast 500—300-mb thickness, and the computed 500-mb temperature were used to obtain a mean temperature for the layer. The 300-mb temperature was determined from the mean temperature and the 500-mb temperature. This procedure was repeated for 200-mb temperatures. TRC regression equations were used to compute temperature forecasts for 300 and 200 mb in Experiment 2.

Using the above information as input data, the 24-hr forecasts of heights and temperatures are computed for the 250-, 150-, 100-, 50-, 30-, and 10-mb levels for Nashville and the four surrounding grid points. Forecast winds are computed from the height values.

E.II Procedure for Generating 12-hr Forecast Profiles

The 12-hr forecast of height, temperature, and wind speed was obtained by linear interpolation between the initial-time data and the 24-hr forecast values of height, temperature, and wind speed (except for the 500-mb level, where geostrophic winds were computed by the program from values of height taken from the 12-hr, 500-mb prognostic charts).

E.III Procedure for Generating 36-hr Forecasts

To obtain the 36-hr forecast values of height and temperature, all computed values of height and temperature for the 24-hr forecast are considered as "past" data; the "present" data fields (required by the equations) are the NMC 36-hr prognostic charts.

The procedure for reading and tabulating height values from the charts is the same as described for the 24-hr prognoses. The 36-hr temperature field forecasts are obtained using the trajectory method for 700 and 500 mb.

In generating the 36-hr forecast, there is no 850-mb, 36-hr prognostic chart available for height and temperature information. To obtain 850-mb data, the following procedure was followed:

(a) The 36-hr sea-level pressure forecast was converted to a 1000-mb forecast by subtracting the 500-mb forecast from the 1000—500-mb thickness forecast.

(b) The 1000-mb temperature was computed from the 1000—700-mb thickness and mean temperature, and the 700-mb temperature.

(c) The 850-mb temperature was determined from the 1000—700-mb lapse-rate curve using the 1000- and 700-mb temperatures.

(d) A mean temperature was computed for the 850—700-mb layer, and was used to arrive at an 850—700-mb thickness.

(e) The 700-mb heights were subtracted from the 850—700-mb thickness to obtain the forecast of 850-mb heights.

Height and temperature data are then complete for the 36-hr forecast for the 1000-, 850-, 700-, 500-, and 300-mb levels, and are the input to the program which uses TRC regression equations to compute the 250-, 200-, 150-, 100-, 50-, 30-, and 10-mb heights and temperatures. Wind forecasts are generated using the heights.